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AUTOMATED SETUP ASSEMBLY MECHANISMS for the INTELLIGENT MACHINING WORKSTATION

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Table of contents

Table of figures

Abstract

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Introduction

Traditional production engineering wisdom states that to economically produce a widget, it should be manufactured in as large a quantity as possible. Since every widget requires a different set of operations and tools, there is an initial cost associated with resetting machines, fixtures, and programs for a new product. A large production volume is needed to recover the fixed costs associated with planning, scheduling, and setting up the machines.

Recently, the goal of reducing lot sizes has been espoused by a growing number of manufacturers. This results in reduced raw, work in progress (WIP), and final inventory, and the ability to respond more quickly to market changes. Also, defects in the manufacturing process can be more easily exposed and corrected when using this just-in-time method. Currently, batch production represents 50-75% of all manufacturing, with 85% of the batches consisting of less than 50 pieces [1]. The typical customer has changed, as well. People are more likely to want their own customized widget, and quickly, too.

This has occurred during a time of reduced enrollment in vocational programs for such trades as machining or welding and cancelled apprenticeship programs at large corporations. The result is a shortage of qualified craftsmen and increased costs for those that remain. There is a severe mismatch between supply and demand for this type of manufacturing employee, and the problem is likely to persist.

At the same time, new technologies such as CAD/CAM, robotics, expert systems, and sensors for quality control have been introduced. Each has made a significant impact on the ability of manufacturers to automate various processes. For the most part, simple tasks in each of the above mentioned domains are in common use in today's factories. Flexible Manufacturing Systems (FMS), integrate many of these technologies, but cannot operate without human intervention. The FMS represents the state of the art of manufacturing automation, but even here, economic lot sizes have been in the 50-100 units per batch range. Human craftsmen build fixtures to hold the differing part shapes during processing, as well as loading the raw workpieces in the machines. This slows down the process and increases the costs and economic lot sizes associated with automation.

Hence, even though batch sizes as small as one unit would be desirable, certain fixed costs remain. Besides setting up the machines, planning the process for a new part (creating programs for the various automated machines) has contributed to this cost. Expert systems capable of process planning are now becoming available. Expert systems for subdomains of a difficult task have been linked to make a more powerful system.

The Intelligent Machining Workstation (IMW) Project

Elements of the Intelligent Machining Workstation

The Intelligent Machining Workstation project (IMW) was developed in order to fill the need for automated machining in extremely small batch sizes, particularly for single unit quantities of substantially different part styles. An electronic description of the initial and final part geometries is input to process planning expert systems, and the final result is a part machined to the desired shape. A number of expert systems generate varying aspects of the final plan. A real time control module instigates and monitors execution of the plan, which includes the use of special automated fixtures and tools to create the part specific fixture configurations. A more detailed description of the IMW is found in the technical reports [2-5].

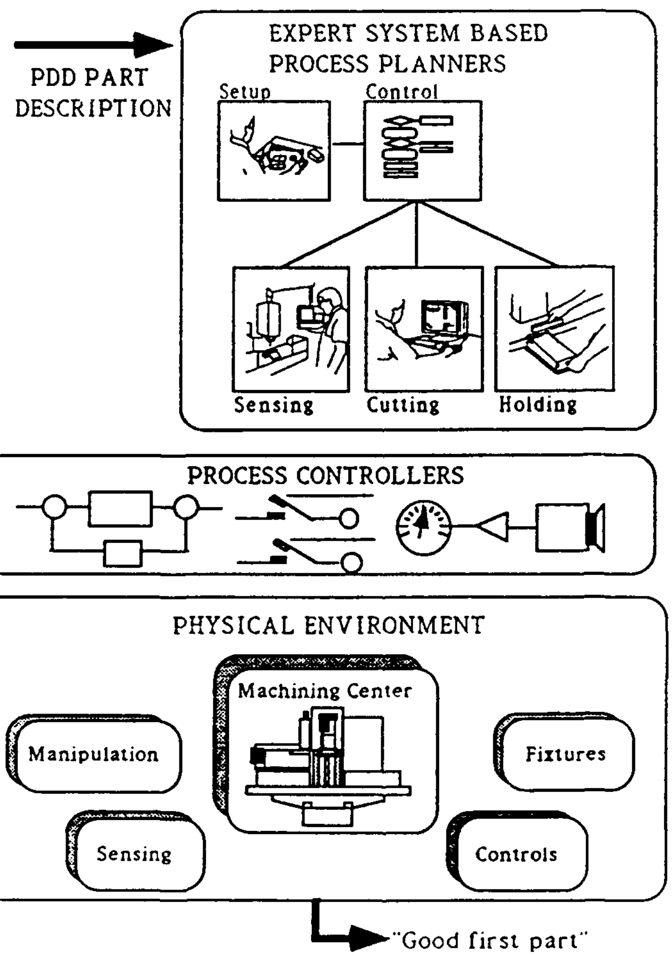

Figure 1- Components of the Intelligent Machining Workstation

Figure 1 illustrates the components of the IMW as three groups: The collection of expert systems that create the process plan, real time controllers to execute the plan, and the physical environment in which a block of metal is sculpted into its final form.

At the expert system level, the physical world and the methods of transforming it are modeled as symbols representing objects. At the process control level, the physical world is a series of electrical events that are measured or applied in order to sense or alter the state of the environment. The physical environment itself forms the bottom layer. Here, motions of tools and cutters produce a series of intermediate forms of the workpiece as it is transformed into the desired final shape.

Process Planning

Each of the expert systems in the IMW resides within a generic expert shell. This way, modules with diverse problem solving strategies running on separate machines have a uniform front end. For instance, one expert system runs on a LISP machine while others are written in C and run on standard UNIX workstations. The generic expert shell allows these different machines to communicate freely. The language spoken between experts is called the Feature Exchange Language (FEL). Geometric, procedural, or physical data can be transmitted in this way. Data is passed to separate modules over an ethernet cable. Besides the five expert systems illustrated in figure 1, two additional modules reside in generic expert shells- the human interface and the geometric modeler.

The geometry of the part is modeled in all of its intermediate configurations between raw and final forms. Other objects, such as cutters and fixture elements, also are described. These objects are represented at different levels of abstraction depending on what module is querying the modeler. The geometric modeler of the IMW is implemented within a generic expert shell and serves as the source of all forms of geometric data for all the other expert systems. This helps maintain consistency in the model between experts.

The part is represented at several levels within the modeler. A boundary representation (BRep) of the part at the lowest level models an object as a series of edges and vertices. The constructive solid geometry (CSG) level merges these into solid shapes such as rectangles and cylinders that can be added or subtracted to yield the object shape. These primitive shapes are combined to form the features that human and computer based experts manipulate symbolically when reasoning about a part. Examples of features are slots, shoulders, holes, and swept cylinders. At different stages of the planning process, information at each of these levels is essential to the creation of the final process.

The Human Interface is the method by which people can interactively enter specifications of the desired workpiece. It also serves as the operator console for the IMW. Until all elements of the IMW have been fully automated, some level of human intervention will be required. For instance, the loading of the stock, and repositioning it for different setups, is still accomplished manually. The Human Interface leads the operator through the required steps and graphically illustrates the desired configuration.

The setup planning expert system is the main result of five years of knowledge engineering. Two experienced machinists were presented with part designs and their thought processes were recorded in order to glean the heuristics they use in creating a process plan [6]. These rules were then used as the basis for a generative process planner originally written in OPS5, which has since been ported to the knowledgecraft™ expert system shell.

The setup planner selects the type of fixture to be used, the orientation of the workpiece in the fixture, and order in which features are created on the part. It is capable of considering features that interact, such as when a hole is located on an inclined surface, or when slots intersect. It can also design new fixture elements or cutters for parts with special needs. For instance, a small part with no parallel sides may be best held on a square plate attached to the workpiece. The output of the planner is a set of ordered process steps that will result in the desired final shape, such as "Place block in vise, side 1 up. Then face mill side 1 to dimension x, side mill sides 2,3 to y, z.."

The cutting and holding experts then fill in missing detailed specifications in their respective domains. The cutting expert in linked to a tooling database that selects the best type of cutting tool for a given material, feature type, and depth of cut. It matches the selection from the database to its list of available tooling. It also selects the spindle speed, feed rate, and depth of cut per pass. Finally, it queries the holding expert for the exact location of the workpiece and fixtures. Using this information it generates the NC code that can produce each of the features as specified by the setup planner. Each setup is considered to be a separate work package.

The holding expert selects a set of fixture components that will immobilize the part, decide where the workpiece should be placed in the fixture, and where the fixture should be placed in the workspace of the machine tool. For instance, the planner may decide that the part should be held flat in toe clamps. The holding expert then supplies the set of vertical and horizontal supports and locators that will insure that the part does not move during machining and is held in a known location. It also selects the location and force applied by the toe clamps. Due to the great similarity between fixturing and manipulation, this module can select grasp points and pressures for dexterous hands [7].

The control and sensing experts were designed to run during both the planning and execution phase. In the planning phase, the control expert is responsible for determining what variables are likely to go out of bounds, using the methods of qualitative physics [8,9]. At this phase, the sensing expert decides what sets of sensors will yield the objective information that the control expert is concerned about. A "virtual sensor" is designed by the sensing expert that will capture the information that the control expert is concerned about. For instance, if the workpiece is of a hard material and a small hole is to be drilled, the control expert may decide that tool breakage is a distinct possibility. Then the sensing expert may decide that the best combination of sensors for a 'broken tool virtual sensor' is an accelerometer and ammeter. The accelerometer measures the vibration of the part , where a lack of any vibration during the cut is a strong indication of a broken tool. The ammeter can gage the current drawn by the spindle motor, which is a function of the torque applied to the cutting tool. A very small current indicates that no load is being applied to the cutter, while a large current suggests that the tool may be jammed in the workpiece, stalling the motor. In the execution phase, the sensing and cutting experts monitor and instigate the physical transformation process.

Controls and physical environment

The process controls and physical environment together form the *craftserver* for the IMW. At one level, it can be viewed as an intelligent peripheral, such as the print spooler and printer are to a computer. In an anthropomorphic sense, it represents the machinist "from the neck down". It consists of the actuators and sensors that interact with tangible objects, akin to the eyes, ears, and hands of the machinist. The craftserver also encompasses the somatic reflexes, knowledge, and coordination that are not part of his or her conscious thought. It is an integrated collection of mechanisms and software that can serve as the physical transformation engine for expert systems. Although the present craftserver has been configured for machining, potential applications of the concept are much broader.

The craftserver has been specifically designed for expert system control of manufacturing processes. Generally, these expert systems contain object oriented information about the techniques, physics, and common sense facts used in the production of parts on the available machines and tools. They send object oriented task requests to a real time program called the Craftserver Task Dispatcher (CSTD). The CSTD then sequences through routines that drive and monitor the physical mechanisms and processes.

A number of novel mechanisms have been developed to support this architecture. Automation of setups is accomplished in a modular environment capable of being transformed by interchangeable tooling. The tools and environment have been engineered to facilitate automated reasoning about them. Finally, new software has been created to communicate with the experts in a format that reflects their own native vocabulary. This permits multiple expert systems to plan, schedule, and initiate the physical transformation processes without having to monitor and control them, or maintain process data or machine specific routines.

The mechanisms of the craftserver that provide for automated setup assembly are the subject of the present report. In the following chapter, some basic fixturing issues are presented, and new concepts are reviewed. The tools used to rearrange the environment are then disclosed. Finally, a new type of fixture base and the components that attach to it are introduced. The architecture of the craftserver itself and the controls that populate it are separately disclosed [10].

Developmental status

The Intelligent Machining Workstation currently handles prismatic parts that are machinable on the three axis vertical NC machining center in our laboratory. This machine tool has a 24 pocket tool drum and tool change arm. We have interfaced to the existing NC controller so that normally interactive commands can be entered through the craftserver interface (see [10] for details of this interface).

The geometric modeler, generic expert package, and human interface are fully developed. A wider range of feature types could be added to the top level of the modeler, however. The setup planner and cutting expert are fully functional and have been demonstrated. The holding expert has been developed but its integration with the other modules of the IMW has not been demonstrated. The control and sensing experts have not been fully implemented, though substantial work has been performed in some of their respective domains.

Introduction to fixtures

Traditional fixturing

Fixturing can be described as the art of selecting a set of locators and clamps and their configuration around a workpiece such that the part is immobilized at a known position and orientation. The part will be subjected to disturbing forces, moments, and vibrations, yet it must remain rigidly supported at a precise position. Processing tools must be accessible to all faces of the part that will be worked on, and unobstructed trajectories must be selected so that the part can be loaded into the fixture. Finally, the surfaces should be protected from being deformed by excessive clamping forces. The single greatest reason why fixturing is so difficult lies in the great variety of potential part shapes and sizes, from simple blocks, to cylinders, slender bars (such as levers), and sculpted surfaces with no parallel sides. The practice of traditional fixturing for machining is described in the technical literature [11,12].

Setting up a part to be processed involves building a fixture from components, inserting the workpiece in it, tightening clamps, and then measuring the location of any degrees of freedom that are not defined by the fixture. Once the part has been set up in this fashion, its location relative to the tools that transform the part will be rigidly fixed and known. Fixtures are used in assembly, particularly for the alignment of components, in welding, die cutting for cardboard boxes, metal stamping and drawing machines, and in machining, to name but a few applications. The accuracy and holding power required is a function of the process being performed. Assembly fixtures, for example, generally have less stringent requirements in holding force and accuracy than do machining fixtures.

Successful design and construction of fixtures for different part sizes and shapes requires compromises between these competing demands. Fixtures are constructed out of elements that locate the part (*passive elements*) and ones that apply forces to the part (*active elements*). These components are usually assembled to a tool base, though they can often be mounted directly to the machine tool. The number of clamps and locators required, and their location in space, is dictated by the geometry of the workpiece. It is desirable to use a minimal number of components so that more of the part's surfaces can be exposed. In this manner, the number of setups needed to perform all the process steps on the part is lowered, as is the part's cost. However, as the number of clamps decreases, the necessary force per unit area increases, making it more likely that the part's surface will be damaged. Tradeoffs such as this are examined in detail be Englert [13].

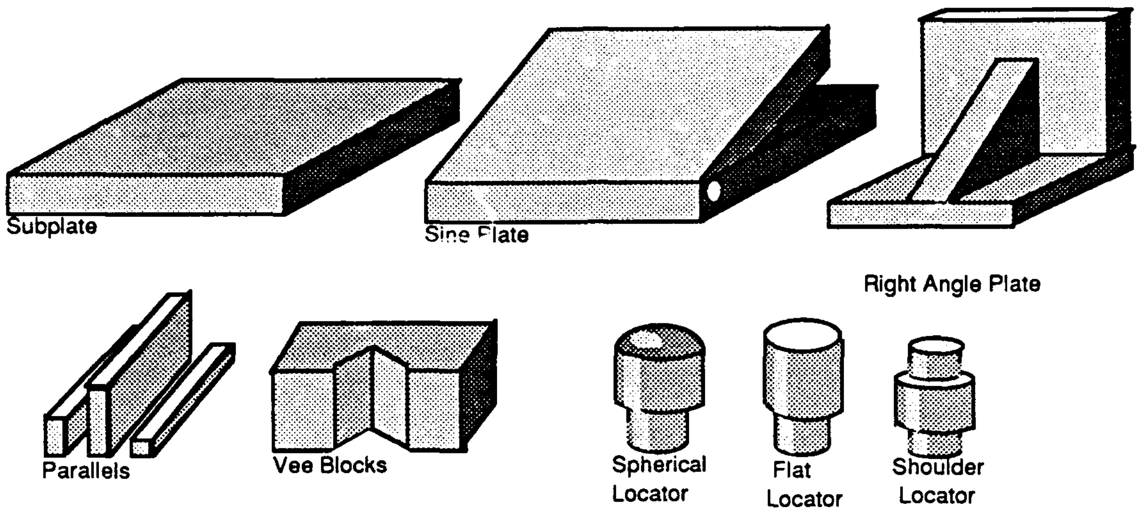

Figure 2- Typical passive fixture components

Figure 2 shows some common passive fixturing elements. The subplate provides planar contact and easy loading of the fixture. When angled features are called for in the part drawing, a sine plate may be used. It reorients the part to any angle from zero to ninety degrees. It is usually set manually. Angle blocks and plates perform the same function but are not adjustable. Parallels and riser blocks can lift the part up a precise amount. Fixed parallels can be used as a fence, to prevent motion in the horizontal plane. Vee blocks give two lines of contact so that cylindrical parts can be held. Spherical and shoulder locators are used to establish a vertical or horizontal position. The spherical locator more closely approximates a point contact. This is desirable when the surface being clamped is wavy, or when holding points are explicitly defined in the part drawing.

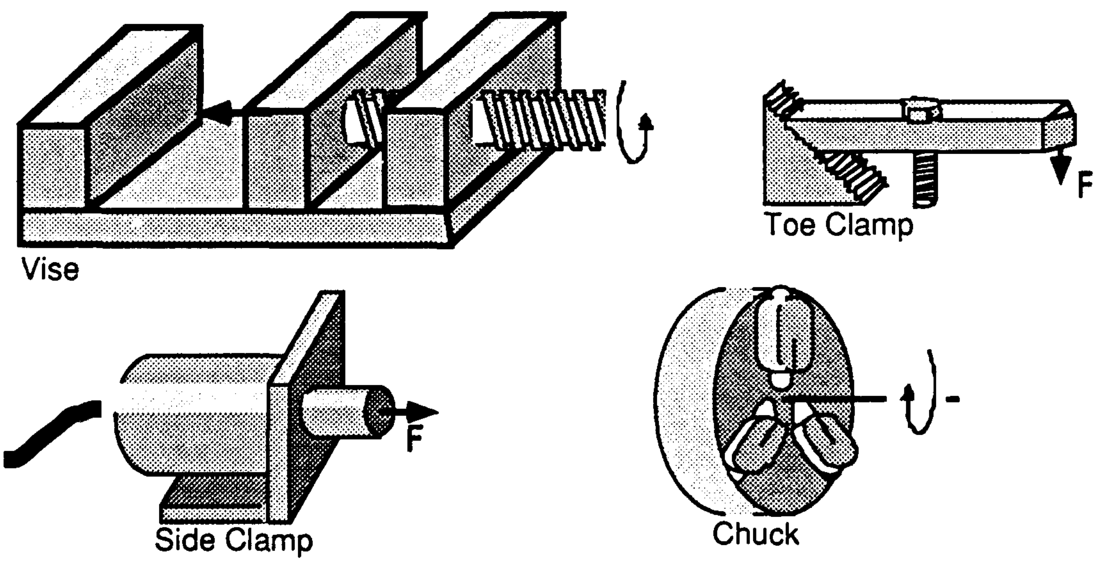

Figure 3- Active fixture components

Active fixturing elements are illustrated in figure 3. The machining vise is a versatile tool capable of both clamping and locating prismatic workpieces. Special jaws can be inserted that conform to irregular part shapes. The vise consists of two halves, one that is fixed and one that moves towards the fixed half. When the vise jaws have a shoulder and one additional stop, all degrees of freedom are eliminated. Under light machining loads, these additional locators may not be necessary. Vises have limited accuracy due to finite rigidity and clearances between the moving members. Chucks provide an analogous function for rotationally symmetric parts. They have multiple jaws that move radially, and, in some cases, independently. Similar to the vise, chucks locate and clamp the part. Since chuck and part are often rotated at high speeds, unbalanced setups can cause excessive dynamic forces.

Toe clamps and side clamps provide a smaller area of contact and do not locate the part. Toe clamps exert vertical forces on the workpiece and are often used when large or irregular parts, such as castings or flat plates, are being machined. Side clamps provide supplemental horizontal forces that support the part against stops. For safety reasons, they are rarely used alone since the part may become dislodged. Ball plungers and similar devices are often used in fixtures to force parts against stops. Their springs accommodate minor variations in the part shape.

Recent developments

Because of the economic value of reducing setup times and costs, basic and applied research has been performed in academia and industry. Researchers have focussed on improving important properties of fixtures. One area of research has been in developing *conformable* fixtures that increase the area of contact for irregular workpiece shapes. The *accessibility* of a fixture is a measure of how many faces of the part are exposed in a given setup, and how easy it is to load the workpiece in the tool. The capacity of the fixture to handle different part shapes is a measure of its *reconfigurability*. Other important qualities for fixtures are *reliability, precision,* and *rigidity.* Reviews of fixturing developments are found in [14,15].

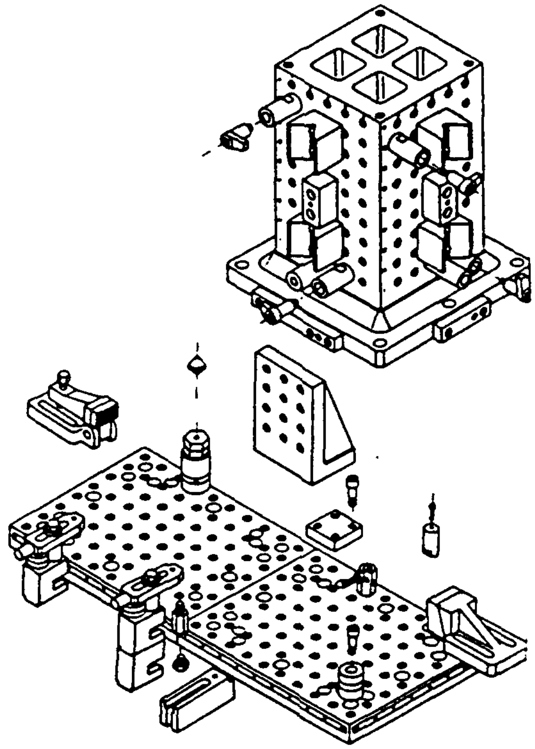

Figure 4- Modular tooling kit setup [14]

Modular tooling systems have been the industrial answer to the need for flexibility in fixturing [15-18]. First developed by the Germans in the 1940's, they are now in fairly common use in industry, and there are at least five vendors of these systems in the market. They are used by tool and die manufacturers, prototype developers, and for other low volume processes. The sets tend to have an large array of components, of different lengths, widths, etc., to accommodate differing part sizes and shapes. The components mount onto tool bases, and tee slots or tapped and bored holes are used to accurately locate and affix the elements. They are assembled manually. The steps required to build a fixture can be recorded, and the final fixture photographed. Gaging and measuring the final locations of the components is also needed in order to precisely replicate the setups later. Modular tool kits are successful and well known but are not currently amenable to automated assembly.

When parts have no parallel sides, they can be held in *temperature induced phase change* fixtures [20]. Turbine blades, for example, are precisely located in empty containers and then the containers are filled with a special molten alloy. The alloy is designed so that it will not shrink or expand when cooled. This allows the blade to be firmly held in the container by the material. This is an example of a highly conformable fixture.

Other interesting fixture designs developed in laboratories have focussed on increasing the conformability of solid clamps. A turbine blade clamp designed at Carnegie Mellon University (CMU) [21] has an octagonal outer profile and a set of laminar supports that conform to curved part surfaces. These "fingers"

are forced against the workpiece by pneumatic action and then are locked in place. They are intended for holding turbine blades. The Adaptable fixtures developed at Massachusetts Institute of Technology (MIT) use a similar finger-like approach to conform to irregular part surfaces [20]. A 4 x 4 matrix of spring-loaded fingers is released by the actuation of a shape memory alloy wire.

The pseudo-phase change fixtures of Thompson and Gandhi [23,24] represent the most conformable novel fixture developed by researchers. A vessel containing spherical particles is 'fluidized' by injecting high pressure air to the bottom of the container. In this state, a workpiece can be inserted in the container. When the air pressure is disconnected, the workpiece is held in place due to its being buried in the particles. It conforms to any imaginable part shape but its holding force and accuracy are unsatisfactory for machining.

Designs that concentrate on the problem of automated assembly include the Automatically Reconfigurable Clamp [25]. This clamp is primarily designed for the vertical support of sheet metal parts that need holes drilled in them. A spring loaded button underneath the part can be released by the grasping action of a parallel jaw gripper. It can then slide along tee slots to a desired position. The height is reset using a ratcheting action. Another project, the Flexible Clamping System of CMU, has clamps that apply a downward force on the workpiece, similar to toe clamps [26]. They lock into any of 99 holes in a tool base through the action of expanding pins, and swing along a helical path to clamp the part to a user-selectable holding force. By using these expanding pins, mounting the clamps reduces to a simple vertical insertion followed by the application of hydraulic power. A stackable washer fixture was developed in England [27,28]. Passive locators of any specified height and position can be created by stacking serrated washers and then bolting the assembly together.

Several computer controlled fixtures have also been reported. Two Numerically Controlled clamping machines of the University of Stuttgart are intended to hold parts in conjunction with horizontal milling machines [29]. These large machines automatically position locators in clamps for different part styles. The principal difference between the two machines is that on the "double revolver", the clamps and supports are repositioned on turntables, while the "translational movement" machine moves these components along linear axes. A computer controlled vise [30] was developed by researchers at National Institute of Standards and Technology (NIST). A number of hydraulic actuators were intended to drive the main axis of the vise, as well as smaller locating stops.

Automated Setup Design and Construction

The design and construction of fixtures is still not automated even in the best Flexible Manufacturing Systems. The lack of a reliable and flexible way to automatically construct setups has meant that this function must be performed manually at off-line workstations. Creation of setups is so cost and time intensive that whole departments and engineering disciplines are dedicated to tooling. A reliable and flexible tooling system can make changeovers between part styles on a manufacturing machine much less painful, to the point where extremely low batch sizes are economically feasible. Any process that uses tooling, including the manufacture of parts out of new composite materials, could benefit from the availability of such a fixture system. In this chapter, research in the two prime aspects of fixturing automation are reviewed, the planning of fixture setups and their construction. The methods used in the Intelligent Machining Workstation are then presented.

Automated setup planning

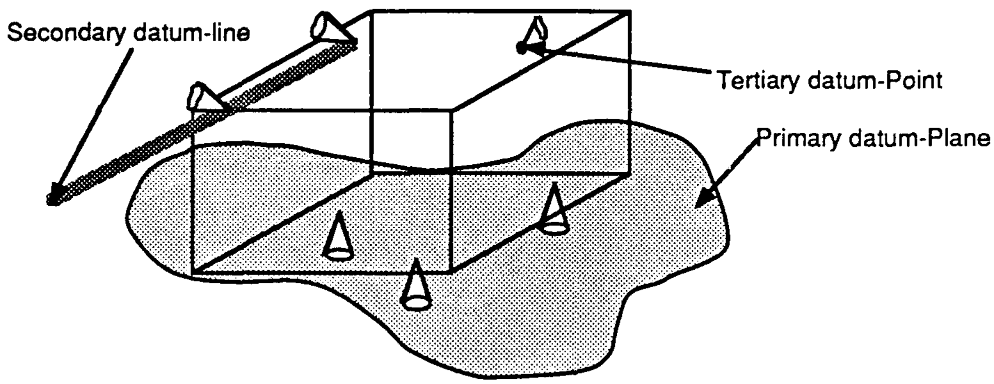

Figure 5- Deterministic positioning example

One of the first tasks confronting the human or computer based fixture designer is to select a set of contact points on the workpiece such that its six degrees of freedom are completely defined. This kinematic analysis and selection is often difficult to do automatically. Human tool designers don't have as much difficulty with this. They use the "3-2-1" rule which states that the part's location is fully defined when it touches a plane, a line, and a point. Figure 5 illustrates this. A plane, line, and point, fully defined by six points (3 + 2 + 1), represent the primary, secondary, and tertiary datums. These datums are often explicitly noted on drawings of complicated parts, since important geometric relationships such as perpendicularity and flatness use them as references. Prototype systems have used the methods to Reuleaux [31] to select these contact sets [32,33], or variational calculus [34].

The contact mode must also be selected. Spherical, conical, line, and flat contact surfaces have increasing area, respectively, which tends to reduce the stress level in the part. However, larger area contacts obstruct more of the surface of the part, and if the part is not sufficiently flat, can cause position errors. The active elements must then be chosen, and their locations about the workpiece need to be determined. The direction and magnitude of the clamping force must be selected for each active element, such that the workpiece will remain stationary as forces are applied by the cutting tools. The screw system formalism [35,36] can model forces or motions and thus is well suited to selecting both the contact set and the set of forces. This has been used by Chou et al. to design fixtures [37].

The rigidity of the workpiece and fixture must also be evaluated. Deflections of the workpiece can cause excessive chatter, or out of tolerance parts. Humans often are successful at qualitative examinations and usually over-design the supporting structures so that the workpiece does not deflect. Automated analysis systems such as [36,37] use the Finite Elements Method (FEM) to evaluate or synthesize the structures of fixtures and workpiece.

The final step is to configure a collection of fixture elements that will result in the workpiece being held with the active and passive contact sets previously selected. Here, providing ample clearance for tool paths and exposing all areas that need to be machined are important considerations. Intermediate configurations of the setup must be available that allow the part to be loaded. Finally, rigidity must again be considered. Markus et al. [40,41] created a system that could automatically design such configurations out of modular tooling elements, using a LISP-based expert system.

The automated synthesis and design work done to date has been fruitful but still is not sufficiently versatile for use in industry. However, CAD-based fixture design programs have been much more successful. Here, the time to design a fixture is shortened by having a database of available fixture types and allowing a human to guide the computer in the more difficult design decisions [42-44].

Automated setup construction

Several development projects have included the automated construction of fixtures. Generally, the location and type of fixture elements used have been described by an operator during interactive sessions. Robots have subsequently assembled the fixtures. However, these systems have either not been flexible enough to handle a wide variety of part shapes or the fixtures have themselves have not been sufficiently strong and accurate for the precise machining of metal parts.

The sheet metal fixtures developed at MIT that have previously been introduced could be assembled using a parallel jaw gripper [25]. The fixture elements were essentially reconfigurable vertical supports that were intended for drilling holes in sheet metal parts. Gordon and Seering [45] developed a method of assembling electric drills using flexible fixtures to guide parts together or to hold one of two mating parts in different orientations depending on the nature of the task. A fixture for machining two dimensional parts was built at the University of Kansas [46]. Here, the instructions for the robot were automatically generated, based upon fixture configurations on a tool base grid that were selected by an operator.

Setup automation in the IMW- The *craftserver*

The planner, holding expert and *craftserver* of the Intelligent Machining workstation work together to plan and construct fixture setups automatically. The holding expert designs the fixtures as previously described, and then downloads object level assembly sequences to the craftserver. The craftserver presents the expert system with a homogeneous array of predefined, reconfigurable modules that establish the environment in which processing takes place, the tools used in those processes, and the methods by which they are used.

The hardware of the craftserver has been designed to simplify the task of the holding expert while allowing for a wider range of possible fixture configurations, and therefore increasing the range of parts that can be held by the system. The machine tool has been substantially upgraded in order to transform it into a setup assembly workstation. Due to the limited amount of workspace, special consideration has been made to reducing the number of components necessary to build a setup. This also reduces the number of fixture elements that the holding expert must consider. The fixture elements, assembly tools, and control routines have thus been simultaneously designed so that they form an integrated system that works together with the holding expert.

The overriding philosophy of the setup assembly system is that a modular, reconfigurable environment that is robust and forgives random positioning and measurement errors is much more likely to succeed. A stable world is defined by the state of all of the devices within the workspace of the machine tool. Transitions between states are accomplished only by tools within this world. Also, all the functions of machining and setup assembly, as well as the storage of fixtures and assembly tools, should be integrated on one machining center. This is a valid assumption for machining parts in batch sizes of one. It is also possible to shuttle the storage racks and plates into the workspace. This would better utilize the space available, and in some future revision, this may be implemented.

A Remote Center of Compliance (RCC) device [47] is used on the system's gripper, and all components are designed to be assembled using snug-fitting pins with a typical clearance of half a mil (.0005 inch). The RCC permits the assembly of components that can be mismatched as much as .100 inch [48]. Once components have been assembled in this way, they are assumed to remain in the manipulated position, which is stored so that they can be retrieved when necessary.

The tools that alter the state of this world are called *novel tools*. They perform non-traditional functions yet they are mounted in the spindle of the machine tool. When a gripper is mounted in the machining center's spindle, the machine tool becomes a 3 degree of freedom (DOF) robot with lifting capacities of thousands of pounds, capable of manipulating to accuracies of better that one thousandth (.001) of an inch. A bolt assembly tool is used to apply clamping forces to parts as well as fastening fixture components to a rectangular grid of holes on a tool base. A third novel tool can reposition a CCD camera along two axes for inspection and gaging of the fixture setup. These novel tools are stored in racks within the workspace of the machine tool. A special adapter, the *standard receptacle* , is stored in the tool drum and loaded into the spindle automatically using the machining center's tool change arm. The standard receptacle can then be approach and attach any of the three novel tools.

The fixture elements themselves are designed to be manipulated and assembled by the available novel tools. Their design was inspired by the modular tooling sets available in industry. The set consists of passive (locating) and active (clamping) elements, as well as the bolts used to fasten them. These are stored on a plate that features another rectangular grid of reamed holes. Passive elements include locator pins, parallels, and riser blocks. Two active components, a vise and toe clamps, are also available. The vise has sensors built into it to monitor the machining process as it is occurring. The toe clamps are designed to have a low profile so as to avoid cutter paths and can be reconfigured by the gripper. Both the toe clamp and vise are actuated by leadscrews that can be driven by the torque tool.

The fixture base restricts the possible orientations and locations of fixture components, while flexibility in the clamping elements provides the variability necessary for successful processing strategies. For instance, the reach of the toe clamps and vise spans the distance between mounting points on the tool base. The fixture base can also be repositioned up to 90 degrees so that it performs the function of a sine plate as well.

For passive fixture components and bolts, the number of different sizes of an given element type that must stored can be enormous, such as the length of a bolt, or the height of a parallel. The craftserver solves this problem by storing only one standard size component and then reducing it to the specific length required as a separate (automatically generated) process step. For instance, if an intermediate setup in the machining of a part requires a vertical support, the specific length required can be generated by stacking standard length supports and then face milling the last support to accommodate the odd dimension. These *machinable fixture components,* reduce the overhead on the expert systems and storage requirements while providing task flexibility. Machinable fixtures are only used for passive components.

Novel tools for setup assembly

Milling machine tools have been constantly improved over the years. Numerical control has become commonplace in production environments where medium volumes of a part style are machined. Servo systems have replaced the mechanical and human actuated motions of traditional milling machines. Controllers and special languages have been developed to take advantage of servo control of the machine tool axes. Automatic tool changers have been integrated into machining workstations, and recently the focus of efforts has been to minimize the time needed to change the tools. The tool changer typically works in conjunction with a tool storage magazine that can hold a large number of cutters. In the machining center used for the IMW, the tool drum can hold up to 24 cutters. They are loaded by a cylinder-actuated gripper that moves between two positions along each of its three DOF.

This has increased the flexibility and autonomy of the machine tool. There is a fixed cost associated with this flexibility, however. Every time a new part is to be machined, the set of operations must be carefully considered, a NC part program then generated, and the program must be tested and debugged before it is considered to be reliable. CAD/CAM programs have decreased this time to a certain extent, but program errors still can be created. These must be identified and corrected. Also, fixtures still need to be assembled and loaded manually. Furthermore, the processes have been initiated and monitored by a human operator.

New devices are being used as attachments to tha machine tool, also. The touch probe [49] is a tactile sensing device that has sufficient precision to measure positions for machining applications. It can be stored in the tool drum and then loaded into the spindle of the machine tool, sweeping the probe along a selected axis. When the probe contacts a surface that is to be measured, sensors in the probe change state and this event stops the motion. The probe is then slightly retracted, and approaches the part once again, at a slower rate. When the probe contacts the workpiece the second time, the servo system is queried for the manipulator's current position. After correction has been made for the diameter of the probe tip, one coordinate of the workpiece's surface in the workspace has been determined. The touch probe is sensitive in 2 1/2 DOF (It cannot measure heights from below).

When a model of the desired part geometry is available, a series of these measurements can be used to determined conformance to part specifications. However, dedicated Coordinate Measuring Machines (CMM) are generally used. In terms of absolute accuracy the CMM will usually outperform the machine tool with probe. Thermal growth of the machine tool components or workpiece is one reason, and another is the lack of a stable tooling base, such as is provide by the CMM's ground slab of granite.

A touch probe mounted in a machine tool thus enhances its capacities, giving it the ability to adjust machine coordinates based upon the actual part position. It is the original *novel tool,* since it is an electromechanical device mounted in the spindle of the machine tool that does not perform the cutting function that milling machines were originally intended to perform. At the Rapid Manufacturing Laboratory, we have expanded this line of reasoning and have sought to take advantage of the strengths and capacities of the machine tool. The machine tool is both strong, capable of applying thousands of pounds of force, and accurate, being able to position a heavy load to better than one mil (.001 inch), as well as being rigid. In a preliminary effort [50], a special gripper was designed that could manipulate the hydraulic clamps designed by Englert [26] at CMU. The gripper was stored in the tool change drum and, when mounted in the spindle of the machine tool, could load these clamps onto the tool base. This transformed the machine tool into a robot, further enhancing the function of the machine tool at a lower cost than would be required to integrate a separate robotic system.

The tool drum was designed to store compact cutting tools and thus space for novel tools is quite limited. During the IMW project, the standard receptacle was developed to circumvent this problem. The standard receptacle is then the only object stored in the tool drum, and more space is made available for cutters. The novel tools are stored in the workspace of the machine tool, so that their size is not as limited. Two other novel tools have been built. The tilt/pan camera mount repositions a CCD camera along two degrees of freedom, and the torque tool permits the automated fastening of bolted connections. It has an electromagnetic chuck that can also be used for manipulation of ferromagnetic objects. These two novel tools transform the machining center into a inspection and assembly station, respectively.

The standard receptacle

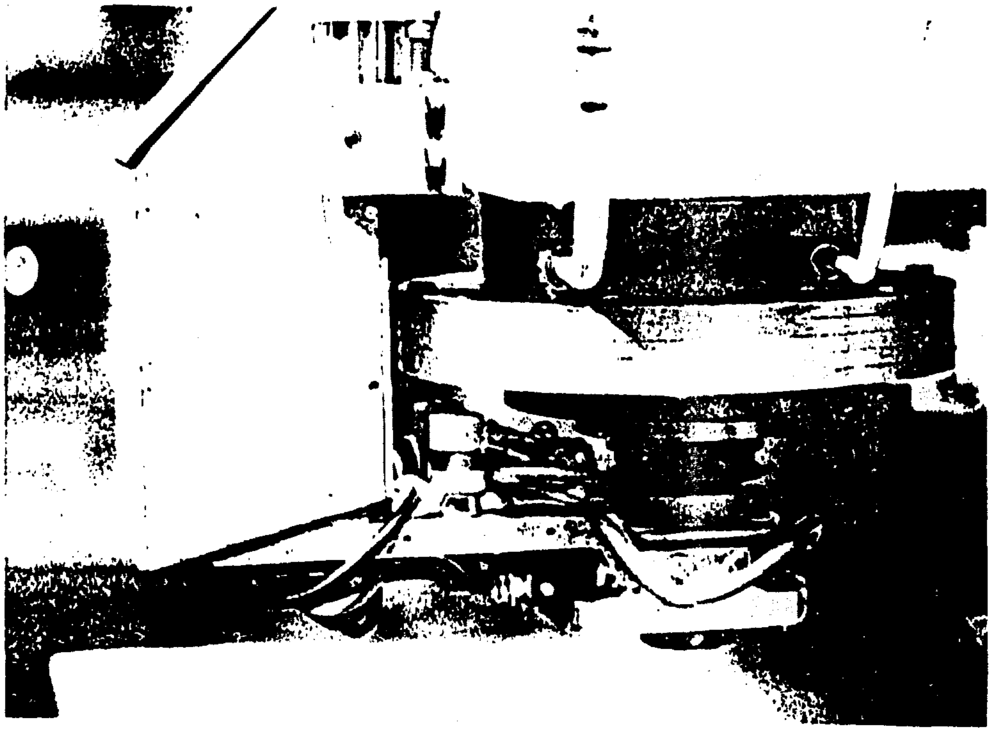

Figure 6-Standard receptacle for novel tools

Three different novel tools developed as part of the IMW project can be coupled to the spindle of the machine tool. The standard receptacle acts as an adapter between the novel tools and the machine tool. It provides electric, mechanical, and pneumatic connections so that the operation of the novel tools can be coordinated with motions of the servo controlled axes. As previously noted, it is stored in the tool magazine, and is loaded into the spindle by a tool changing arm. The novel tools are located within the machine tool's workspace in special racks. They are suspended in these racks by shear pins that can break off if programming errors or mechanical failures occur, thus avoiding extensive damage to them. This same connection method would work equally well on a robot or other repositionable manufacturing machine.

In figure 6, the standard receptacle is shown while connected to the spindle. The light colored trapezoidal enclosure is called the coupler box. It is mounted to a shuttle mechanism that is permanently attached to the spindle carrier. The coupler box has a number of connectors within it that mate with the upper end of the standard receptacle. Service lines attached to the connectors then snake back to controller boxes. Hinged doors keep chips and other contaminants away from these connectors when it is not in use and machining is taking place. The coupler box slides up and down on two shafts

and this motion is actuated by a pneumatic cylinder. A four way valve directs air flow into the appropriate side of a double acting cylinder. The shuttling motion is necessary both for successful insertion of the multiple connectors, since the receptacle cannot mate to the connectors in the coupler box until after it has been secured in the spindle. Another purpose of the shuttle is to retract the coupler box during machining, since it extends beyond the bottom of the spindle carrier and can interfere with fixtures and the workpiece.

The connection between the standard receptacle and novel tooling is performed by a commercially available [51] tooling adapter. The adapter consists of a master half that is mounted on the receptacle and receivers that are attached to the novel tools. Three balls are forced outwards to lock the master to a receiver and thus connect twenty five spring loaded electric pins and nine pneumatic lines. The master and receiver have been modified to include a coaxial connector for video signals. Three solenoid air valves and a relay are used to lock and unlock the coupler, and to control air flow to the novel tools. The standard receptacle and coupler are electrically isolated from the machine tool so as to avoid unwanted ground loops.

The electric signals must be multiplexed since there are more connections needed than the standard product provides. This is accomplished by cascaded 32 pole, single throw relays. The switched lines are of the generic types 'signal' and 'power', where the former are conducted in a shielded cable and the latter are conducted in wire of a thicker gage. The needs of the craftserver were for 9 power, and 16 signal lines, as well as pneumatic air supply and the video signal.

Receptacle detailed design description

This description refers to figure 7. The spindle carrier #1 is the member of the machine tool that moves in the vertical direction and houses the motor and transmission that rotate cutting tools on the spindle, item #2. A coupler box (assembly of items #10-21,25-28) passes electric signal and power lines, video and pneumatic connectors. This coupler box is moved up and down on the spindle carrier by the shuttle assembly, items #3-9, 22-24. The standard receptacle, items #29-45, is stored in the tool drum of the machine tool and loaded by its tool changer arm. This receptacle can mate with novel tools in order to connect them in all necessary ways.

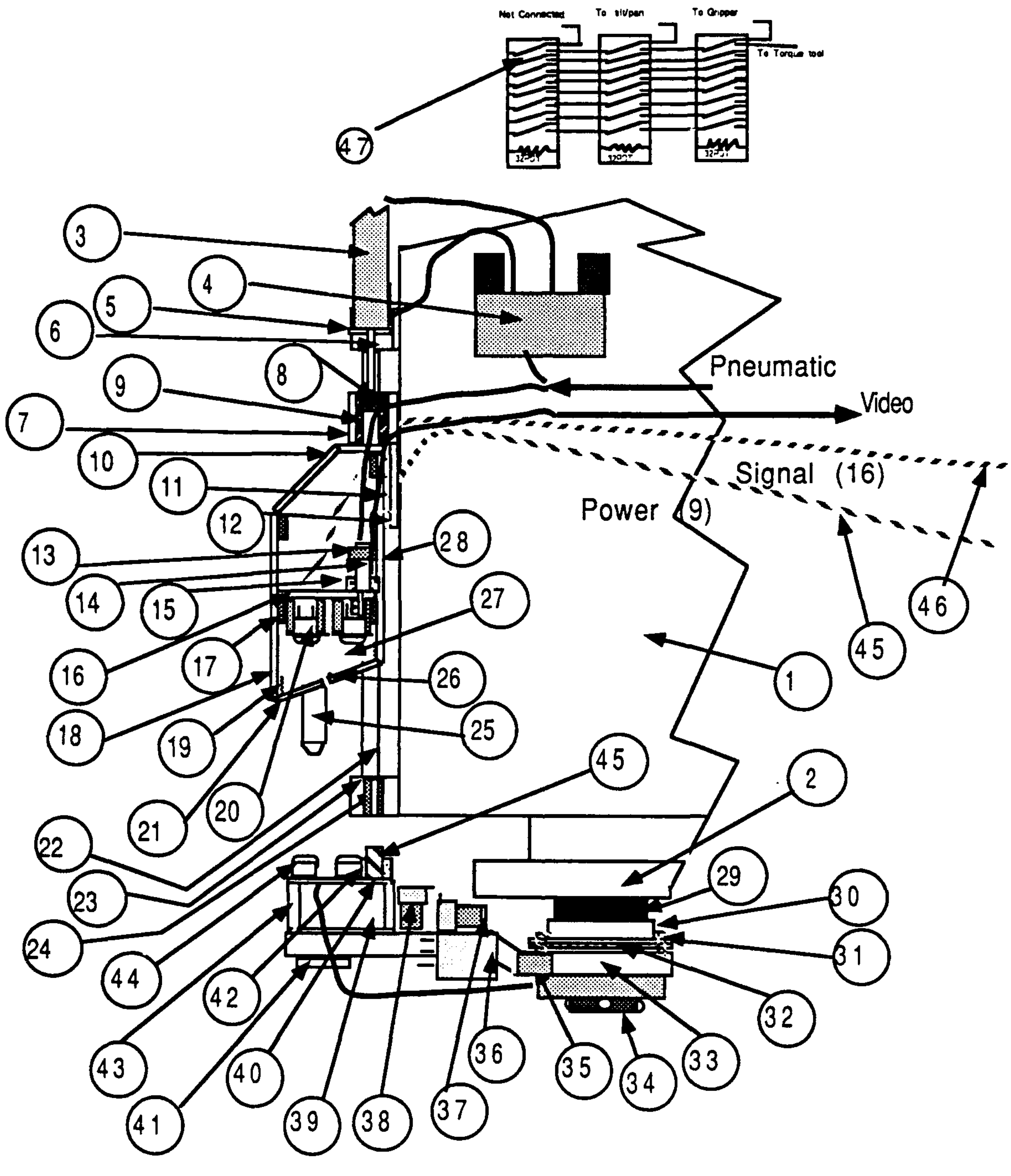

Figure 7- Coupler box and standard receptacle in spindle carrier

One result is that multiple novel tools can be connected to the same signal and power lines, items #45 and #46, respectively. They are fed into a series of cascaded, 32 pole, double throw relays #47. The state of these relays determines the circuit path from the standard receptacle to the various electronic devices needed to drive and control them. As shown on the top of figure 7, the first relay switches between the second and a 'not connected' state. This is to provide a default state of having none of the circuits

connected. Having the wrong circuit path between novel tools and electronics is very hazardous, and this gives some degree of protection. The second relay switches off up to 32 lines (though only 25 are used) to the circuits that control the tilt/pan novel tool. The last relay switches between gripper and torque tool electronics.

The shuttle assembly is pinned and mounted to the spindle carrier by way of top and bottom mounting bars items #6 and #23. Two shafts #22 span these bars, and the shuttle plate #7 is free to slide on them, using bushings #9 to reduce friction and play. The shuttle plate is repositioned by the double acting cylinder #3, and they are connected by a small adapter block #8. The cylinder is fixed on the top mounting bar by a bracket #5, and 4-way solenoid air valve #4 switches the flow to either side of the piston. The torque resisting stake #25 is also fixed to the shuttle plate #7. The shuttle plate is further restrained at the bottom of its stroke by two slotted bushings #24.

The coupler box is mounted on the shuttle plate #7 and is electrically insulated from it by insulation plate #11 and bushings #12. The box itself is constructed out of two side plates #27, front plate #18, rear plate #28, and top cover #10. They are connected by 8 small, tapped blocks #17. Trap doors #21 and #26 can swing open due to two hinges with a torsion springs in them #19. A floor plate #16 holds all of the connectors in place. The delrin coaxial connector holder #14 affixes a modified standard coaxial connector. The pneumatic double-shutoff quick connect #14 is held against the rear plate by bracket #13. Signal and power electrical lines are conducted to two compliant connectors #20, and these are held on the bottom of the floor plate #16 by thru standoffs. Thus the video and pneumatic connectors are fixed in space but the electrical connectors float, thus allowing for some misalignment compensation.

The standard receptacle is held in the spindle carrier by a modified 40-taper V-flange adapter #29. The main receptacle plate #33 is mounted on the V-flange holder by the adapter piece #30, and insulated from it by delrin bushings #31 and mycarta plate #32. The novel tools fit into the master adapter #34, a commercially available product. Items #30, 32, 33, and 34 are pinned together by roll pins so that the orientation that successfully aligns the device to the coupler can be repeated after repair or disassembly. The box which holds the connectors and fits into the coupler box is formed out of two L-shaped pieces #43 and #40 and two side plates #39.

Two male electrical connectors #24 conduct the electric lines to the master adapter #34. Pneumatic connector #45 supplies air to three 3-way solenoid pneumatic valves #38. Two valves and a DPDT relay #36 are used to switch air between the lock and unlock ports on the master adapter #34. A third solenoid is mounted on a bracket #37 and controls the airflow to a pneumatic port on the master adapter. This air is used by the pneumatic

circuits on novel tools. The delrin video connector #42 holds another modified coaxial connector and is conducted through quick disconnect #35 to another coax connector which conducts the video signal from the CCD camera of the tilt/pan novel tool. Excess torque is restrained by torque bar #41 which has a delrin bushing in its hole so as to be electrically insulated. This bar mates with the stake #25 affixed to the shuttle plate.

Gripper novel tool
Manipulation issues

Many industrial and mobile robots use grippers to change the position and orientation of objects within their ranges of motion. Manipulated objects can differ vastly in size, shape, composition, and weight. Knowledge of the initial and final positions of the object are subject to uncertainty, as are the motions of the manipulator. Grippers are designed to perform the manipulation of particular classes of objects.

The most common gripper has parallel jaws which close in around the part. As the part is trapped by the jaws it aligns itself with them, provided the error angle is small and the jaws open wide enough to accommodate it. However, knowledge of the position of the part within the jaws then becomes more uncertain. Parallel jaws dictate that the part must have parallel sides, which limits their usefulness. Other grippers use scissor action, or other more complex kinematic linkages that enclose the object. Anthropomorphic grippers, such as the Utah/MIT hand, try to replicate the design of the human hand [52]. This results in more dexterous manipulators but also increases the difficulty in selecting grasp points and positions for each programmable axis of the fingers. Other special purpose grippers use suction, magnetic fields, or adhesion to grasp the part. A more complete discussion of gripper designs is found in [53].

A number of decisions are associated with the design of a successful manipulation strategy for a particular object in a specific environment. The gripper must be selected, as well as the grasp points and sequence, contact force, and motion vectors. Kinematics, dynamics, and geometric modeling have been used by robotics researchers to develop a foundation for generalized manipulation strategies. Sensing techniques have been used to reduce uncertainty. While general purpose robotic manipulation systems have been built, they have not been simultaneously both reliable and flexible.

The bulk of manipulation applications in industrial practice have been developed for volume production of parts within a family of styles that is fairly limited. Manufacturing engineers select grippers and debug holding strategies so that specific parts styles can be manipulated at economical levels of speed, precision, and reliability. Thus, in practice, manipulation flexibility has been limited. This has made changing from one workpiece to another more difficult and costly, contributing to a lack of truly flexible assembly workstations.

The expanding finger gripper

The expanding finger gripper was designed to fill the need for a device that can hold a wide variety of objects and be able to manipulate objects both reliably and precisely. Besides being used as a novel tool in the IMW, this gripper could be mounted on an industrial robot. It is primarily intended for the assembly of fixtures or other setups, but could also useful for assembly of finished components. It can hold a great variety of objects shapes. It allows human or computer experts to avoid extensive reasoning about the holding strategy, It represents a practical solution to general purpose manipulation, sidestepping many of the difficulties of the general manipulation problem.

Any object that is to be held by a gripper must have a *manipulation feature* that matches its capacities. For instance, parallel jaw grippers must mate with prismatic parts (with parallel sides) of the proper dimensions. The expanding finger gripper broadens the range of permissible part shapes. The manipulation feature for this gripper is a hole. Any object shape that includes a hole of the proper diameter can be manipulated by it. The finger gripper is inserted into this hole and then forced to expand. A widely diverse set of objects can be presented to the gripper with a hole in them, thereby making them manipulable.

A very reliable manipulation strategy is "peg in hole" insertion. In this mode, either the peg or hole is assumed to have a chamfer to guide the peg (or finger in this case) into the hole [47]. Once inserted, the position of the pin is known to an accuracy related to the diametral clearance between pin and hole. Practical values of this clearance are sufficient for most fixturing applications.

The RCC helps prevent jamming by decoupling angular from lateral displacements as the peg is guided by the chamfer. If the guiding chamfer shifts the pin's radial position, the angular orientation is not altered, and vice versa. This decoupling is accomplished by elastomers that are quite stiff in compression while being laterally compliant. The ratio of these two stiffnesses and the angle at which they are mounted at establishes the distance to the *center of compliance* [54]. The decoupling is most pronounced at the center of compliance, which is projected a specific length in front of the lower plate of the RCC. Hence, the assembly length should be tuned so that the forces associated with the chamfer crossing are applied at this center of compliance. The RCC can also guide the simultaneous insertion of two pins, in which case all degrees of freedom of the object can be precisely defined.

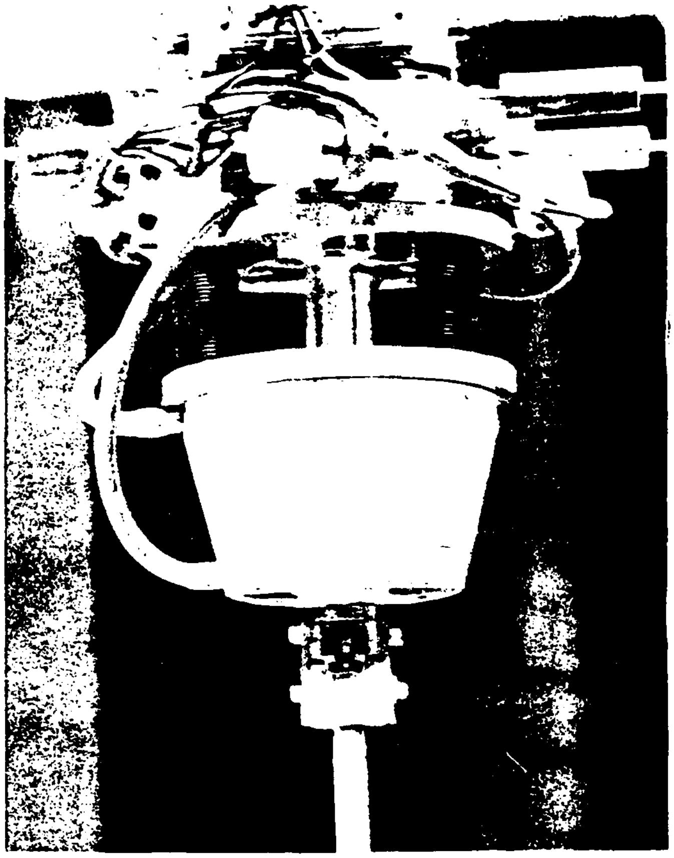

Figure 8- Gripper attached to a machine tool

The gripper consists of two concentric air cylinders that are used to actuate and reposition the finger (see figures 8,9). One motion actuates the finger, which consists of an expanding bushing. The other raises or lowers the first cylinder and the output shaft assembly. These cylinders are mounted on the lower plate of an RCC. The RCC guides the finger towards the center of the hole. Once the finger has been inserted, the center air cylinder is charged, causing the core pin of the expanding bushing to retract. Spring steel rings and cones are stacked on this core. The retracting pin causes the diameter of the rings to increase, thereby holding the part.

The diametral travel of the expanding bushing determines the minimum and maximum allowable hole diameter for successful grasping. The finger most often used has a .375 inch diameter with a .015 inch expansion. Interchangeable fingers can be attached to the end of the griper, in a range of different diameters and lengths. The gripper itself can be mounted on a wrist so as to be able to articulate in all six degrees of freedom, though the prototype only moves in the three degrees of freedom provided by the machine tool.

The assembly of object and gripper can then be relocated to the accuracy of the manipulator. In cases where the manipulated objects have pins or other mating features, the RCC is used again to guide the object to its final destination, where precise holes define the final position into which the part mates. In the case of the fixture components of the IMW, two pins are used to

fully establish component's horizontal location on the tool table or storage plate. The RCC and expanding finger work together to form a manipulation technique which is precise, reliable, and versatile.

The RCC requires that the contact forces occur close to its center of compliance, yet the objects differ in the distance between gripper hole and mating feature (such as pins on the underside). Also, the contact forces are at the fingertip during the grasp phase, while they shift to the object's pin tip during the placement phase. This is solved by using the outer cylinder of the gripper to shift the axial position of the fingertip so that the contact forces occur near the center of compliance. The retract/extend feature also opens up the way to a second mode of manipulation, namely the pushing or tapping of a part. Judicious pushing motions can insure that a part contacts its full set of locators. This is useful in setting a part in its fixture. By regulating the pressure of the air entering the outer cylinder, an automatically adjusted range of forces could be used for these pushing motions. While the prototype has no such regulator, it could be installed.

In light of the field of design for manufacture, it is easy to see how many commercial parts and assemblies could be slightly modified by the addition of a hole, while others may already have one. The setup assembly workstation that has been developed as part of the IMW is configured on a machine tool, so in this specific case, parts without holes can be drilled to suit. In situations where a hole is undesirable, the area around the hole could be removed as a final process step. Simply put, the addition of a hole in the parts can make automated assembly feasible. Many manufacturing engineers would perceive this as a reasonable tradeoff.

Gripper detailed design description

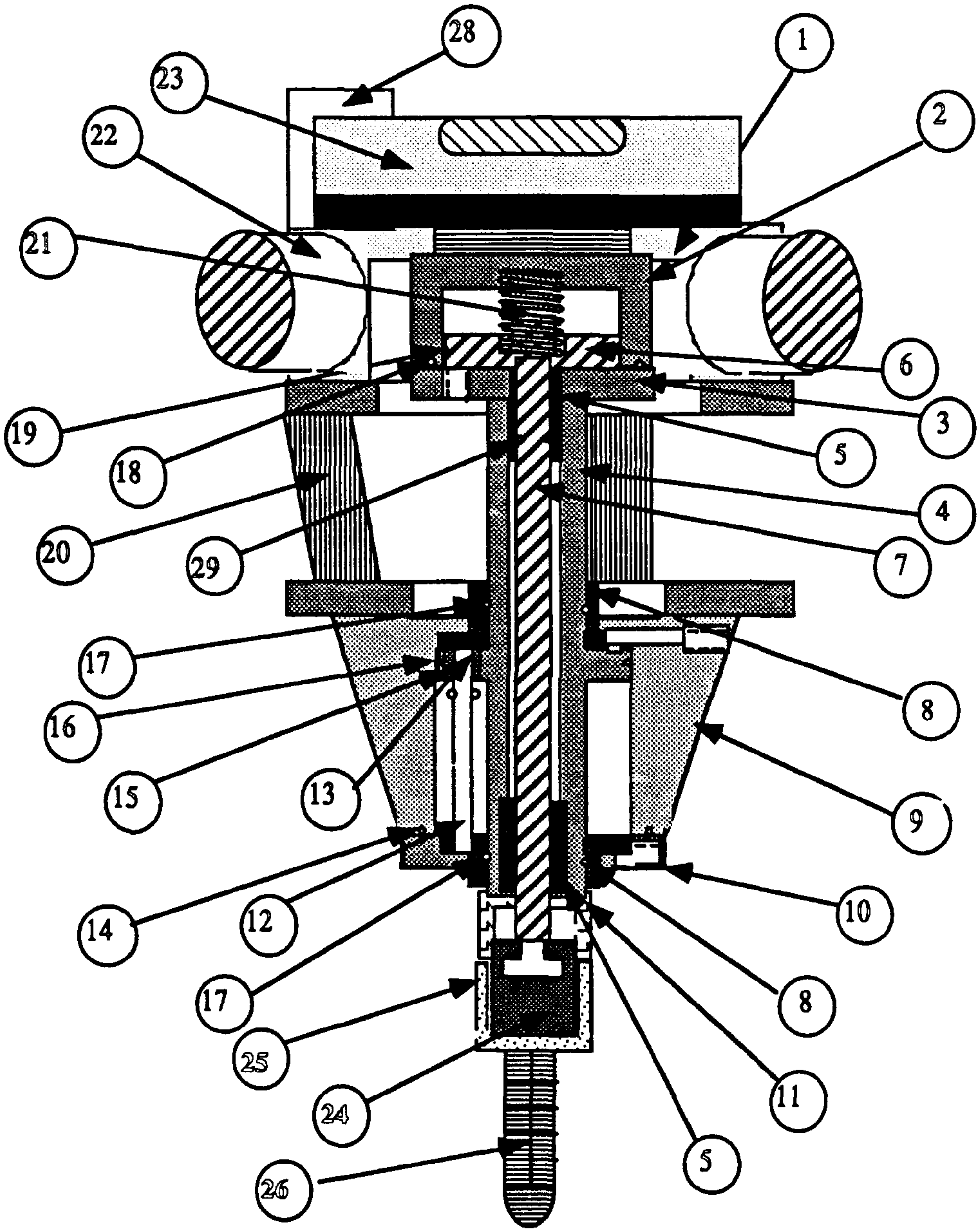

Figure 9- Cutaway view of gripper

The finger gripper consists of two coaxial pneumatic cylinders mounted on a commercially available, modified RCC item #20. A tripod shaped piece (#1) holds three 3-way solenoid air valves (#22), a relay for the extend and retract air valves (#28) , and a receptacle for mounting it to a manipulator (#23).

The cylinders are configured to take advantage of the area in the center of the RCC. The inner cylinder is spring-returned, and has as parts the cup (#2), piston (#6), cap (#3), spring (#21), and O-rings. The piston drives core pin (#7), which is guided and sealed by bushings (#5). The core pin passes through the piston for the extend/retract cylinder (#4), and the cap (#3) is affixed to it, so that the inner cylinder moves with the piston. The extend/retract cylinder (#9) has bushings (#8) to guide its piston (#4), while anti-rotation pin (#12) keeps its orientation fixed. This A-R pin passes through a bushing (#13) pressed in to the piston (#4) and it is sealed by an O-Ring.

The gripper push bracket (#11) has open ends on two sides so that the gripper can change its attachment with a lateral motion (into/out of the plane of this figure). The finger attachment illustrated is built up out of a grip head (#24) which mates with the core pin, the ring and cone expanding bushing stack (#26), and finger push bracket (#25). When the core pin of the gripper retracts, the two push brackets engage and compressive forces are transmitted to the cone and ring assembly (#26), thereby causing the bushing to expand and grip on the inside of the manipulation hole.

The torque tool

The application for which the torque tool was developed was the assembly of fixture components. Different workpiece styles produced on the same processing equipment require flexibility in fixture configurations. This setup phase must be automated for fully unmanned part production. The torque tool, in coordination with new fixture components, is intended to successfully create such setups, by assembling and reconfiguring the fixture elements to suit a variety of part geometries and operations.

In many machines and manufactured goods, bolts, nuts, or other threaded fasteners are used to assemble components. To date, few FMS workstations have assembled bolted components due to difficulties in matching the alignment of the male and female threaded parts, acquisition, manipulation, and retrieval of the fasteners, and the difficulty of following bolts down their helical path.

The torque tool is the primary tool in a new method for assembling threaded fasteners. It can also be used to drive a leadscrew or reduction gear, thereby providing a flexible tool for linear or rotary repositioning. Devices moved by the torque tool can be driven precisely in position, speed, and applied force. One torque tool can drive many such devices. This obviates the necessity of power conduction to each individual mechanism, such as hoses for pneumatic or hydraulic cylinders, or cables to electric motors. Instead, one tool applies power to all devices and relies on friction to hold them in their final position. Being under program control, the torque tool can recall these positions at any time and change them again. This considerably widens the flexibility of automated assembly and processing tasks without increasing the costs associated with them.

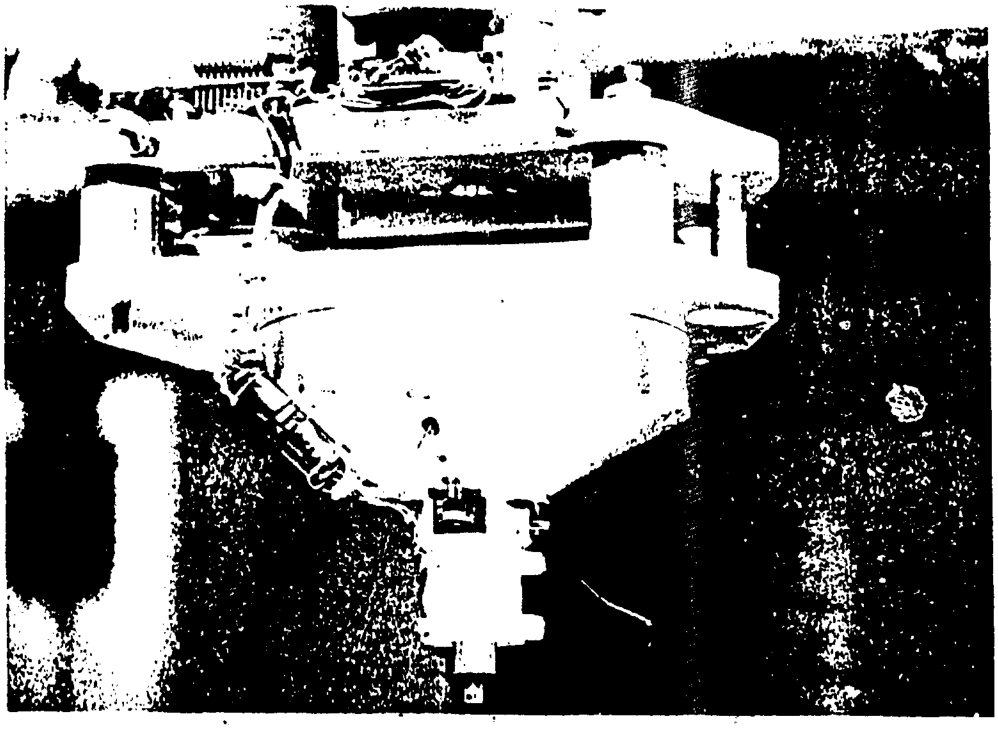

Figure 10- Torque tool

The torque tool is driven by an electric motor under servo control. It accepts a number of different attachments so as to be able to drive different types of fasteners (see figure 10). The position of its shaft is sensed using an optical encoder, which is used along with a commercially available servo controller to allow the shaft position, velocity, or torque, to be set or reset, under programmable motion characteristics. The motor shaft drives gearing that reduces the speed of the output shaft, currently by 150:1, using harmonic and spur gears.

The torque tool relies on a manipulator such as a robot or machine tool to move it in space. It must coordinate its own motions with the manipulator in order to follow the helical path of a driven fastener. Since it is a novel tool, it has a receptacle on its top plate, to connect it to the standard receptacle. An electric coil is wrapped around the driver on the bottom of the torque tool. When energized, this coil turns the attached driver into an electromagnet that can hold and manipulate fasteners or other ferromagnetic objects.

It has two parallel plates that move relative to each other in order to give compliance at the tool tip. The plates are connected by elastomeric discs that are preloaded by bolts. These bolts are fixed on the lower plate and apply pressure to a stack of washers between the bolt head and the upper plate. The stack consists of a nylon flat washer and spherical washer set. Two pins on the top plate mate with slightly oversized, chamfered holes on the lower plate. This allows the top plate to shift radially relative to the lower plate and rock the plates out of their parallel position, while preventing twist around the bolting axis. Hence, the pins resist motion about the torque axis, while [illegible]

tool tip is compliant radially and in angle of orientation. The compliance lets the fastener find its way into its mating threaded hole, in the presence of uncertainty in tool tip alignment or position.

The attachments connect to a spring loaded member whose axial position is sensed, currently using a limit switch (proximity switches could also be used). By monitoring the deflection of the spring loaded member, commands to the manipulator can be generated in process so that the torque tool follows the fastener into its threaded hole. It is also used to detect error conditions. For instance, if the a bolt is not in the assumed position, the state of the spring loaded member can indicate if jamming is about to occur or if the bolt is not present. If another object is in the way, the member deflects and this can be used to prevent the tool from crashing into that object. A small amount of "overtravel" is built into the switch and spring assembly to assure sufficient reaction time to stop the motion of the tool.

Fasteners are stored in threaded holes on the storage plate, so the generic assembly operation is unscrew-reposition-screw when either assembling or removing bolts. During unscrewing, deflection of the spring loaded member signals the robot to start moving up the axis. If the member returns to the undeflected position, the tool is retracting too quickly and its motion can be paused. Unscrewing is finished when the torque tool goes one revolution further than the number of turns that were stored by the program during the last unscrew-screw cycle.

With unscrewing done, the electromagnet holds the fastener in place, and it is moved over the destination hole. The final approach is at a slower rate, and it is stopped when the bolt contacts the hole, as noted by the spring loaded member. Thus there will exist some spring pressure between mating components. This pressure and the tool tip compliance allow the threads to fall into line when the torque tool starts its clockwise (screwing) rotation. The feed downward is started when the spring is no longer deflected. The motor is driven in torque mode, which sets the maximum output torque, and then the velocity of rotation is monitored. When the velocity reaches zero, maximum torque has been applied and the bolt has been torqued to specification. The downfeed is then stopped, the final rotary and axial position of the bolt are read and stored.

Experimentally, the compliant plates and spring member have never failed to align bolt and hole, with no damage to the threads. Currently, the maximum speed of the torque tool is somewhat slow, but this can be corrected. We have used both custom fasteners with extra-deep phillips heads as well as standard socket head cap screws. Hexagonal cap screws should also work well, as well as phillips and torx heads, while straight slotted fasteners may be problematic. Fasteners whose attachment features are deepest work best.

Torque tool detailed design description

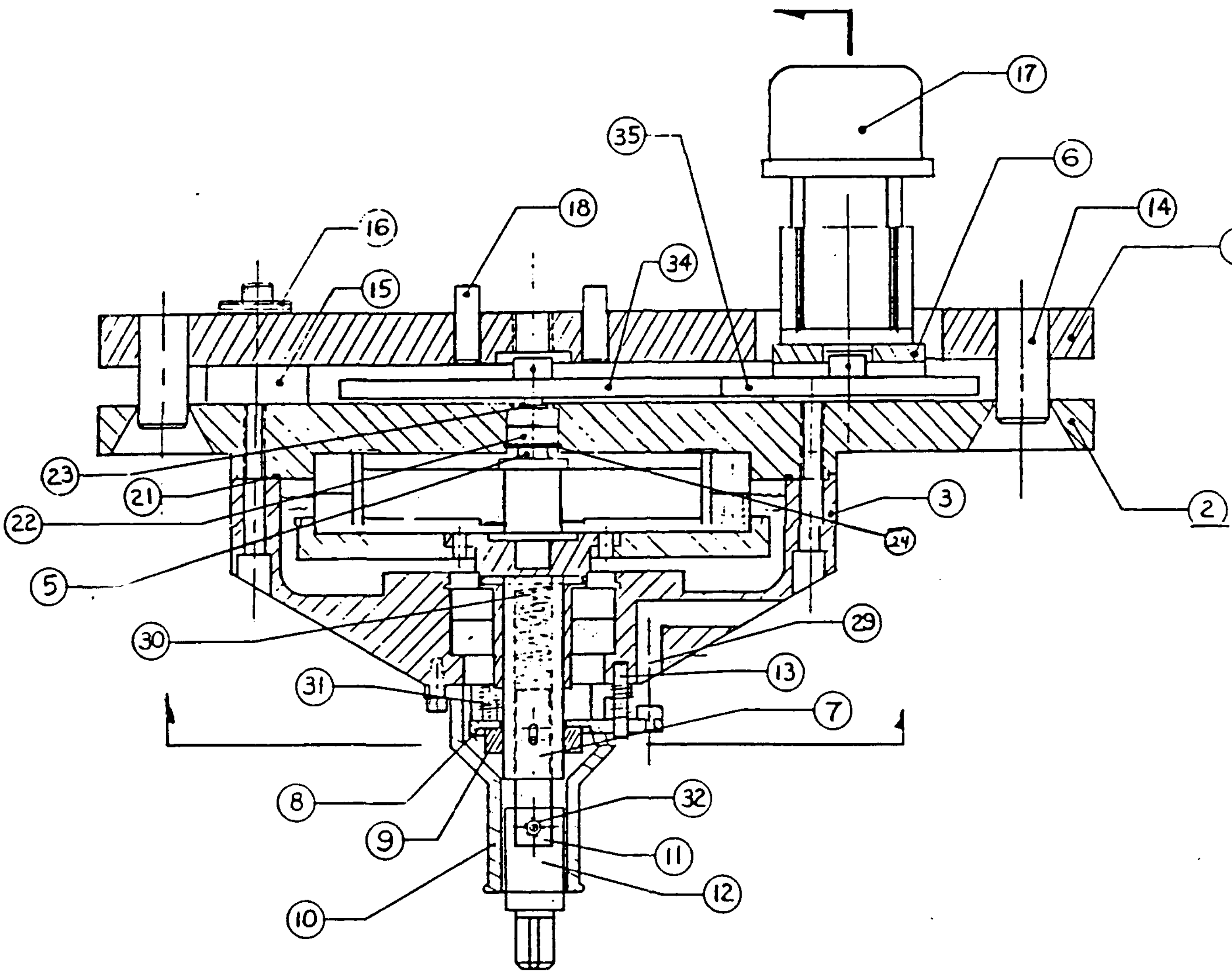

Figure 11- Cutaway view of torque tool

The top plate (#1) has pins (#18) with which to mount a receiver for the standard receptacle. Larger pins (#14), along with elastomers (#15), and the bolt and washer assembly (#6), provide compliance between top and bottom plate (#2), and by extension, between the robot and the tip of the fastener to be assembled.

The electric motor with shaft encoder, (#17), drives a pair of spur gears (#34,35), which in turn drive the input shaft (#5) of the harmonic drive. The

electric motor is mounted to a bracket (#6) which is attached to the lower plate (#2). The harmonic drive sits in an oil filled cup (#3), fixed to this plate. The output ring of the harmonic drive is attached to a plate with a slender tube that has a square hole affixed to it (#30). Input and output shafts are captured with thrust and radial bearings, and a seal keeps the oil from leaking out.

Spring member (#7) sits in the square hole of the output plate and is captured by a pin that goes through its center and also spans the square hole. This same pin attaches to a ring (#9) around the square hole tube. Thus the ring travels axially and rotates with the spring member (#7). A spring loaded plate (#8) is fixed to the oil cup with three pins (#13). The ring (#9) rubs against this plate, while a position sensor (#29) detects its motion, and by extension, the fastener connected to the driver attachment (#12). This driver directly connects to the spring member and is locked by a ball and spring plunger (#32). An electric coil is wrapped on the lower part of the electromagnet cone (#10). When energized, the coil turns the attachment into a magnetic core whose field is still sufficiently strong when the attachment protrudes from the cone by two or more inches.

The tilt/pan

A fully automated machining workcell may need the capacity to visually monitor the process during each phase of the environment's transformation. Before machining, the fixture setup can be inspected so as to insure that all components were properly assembled. Machine vision can be used to confirm that the part has been properly seated against its locators. It can also perform coarse measurements of the location of the workpiece when its position is not well known. Subsequent use of the touch probe can then yield precise locations without the need to sweep wide areas of the workspace in search of the part or risking damage to the probe tip. During machining, the presence of coolant and tools can be checked, and the type of chip being generated can be inspected. Post process inspection of the part may be accomplished.

One of the advantages of performing measurements using machine vision is the flexibility available in the precision and range of those measurements. Though the camera itself has only a fixed number of pixels available to perform measurements, repositioning the camera allows for variability in range and precision. When the distance between the camera and scene is increased, the field of view of the camera is increased and it can scan large areas quickly. Interesting features within that scene can be more precisely measured by moving the camera closer to specific areas. In order to be able to relate the location of objects within the scene to global positions, the location of the image plane must be known precisely. Here the intrinsic accuracy of the machine tool can play an important role in assisting in these measurements.

Image understanding is a complex undertaking in any environment and though the machine tool workspace is more limited in scope it is still a difficult problem. It was anticipated during the initial phases of the IMW project that sensor understanding research would play a major role in the final implementation of the workstation. Preliminary work conducted by Goldstein at CMU [55] indicates that tool wear can be measured using vision. Hardware for image collection and processing was purchased and the need to integrate it into the systems of the IMW was established. Within this framework, it was determined that a reliable, precise method of mounting a CCD camera within the workspace of the machine tool was needed. The tilt/pan was developed to provide a modular base for a small CCD camera and the ability to reposition it about two axes, namely in the tilt and pan directions. It is fully operational and it is able to collect images of the machining area. We now have an environment suitable for further vision research.

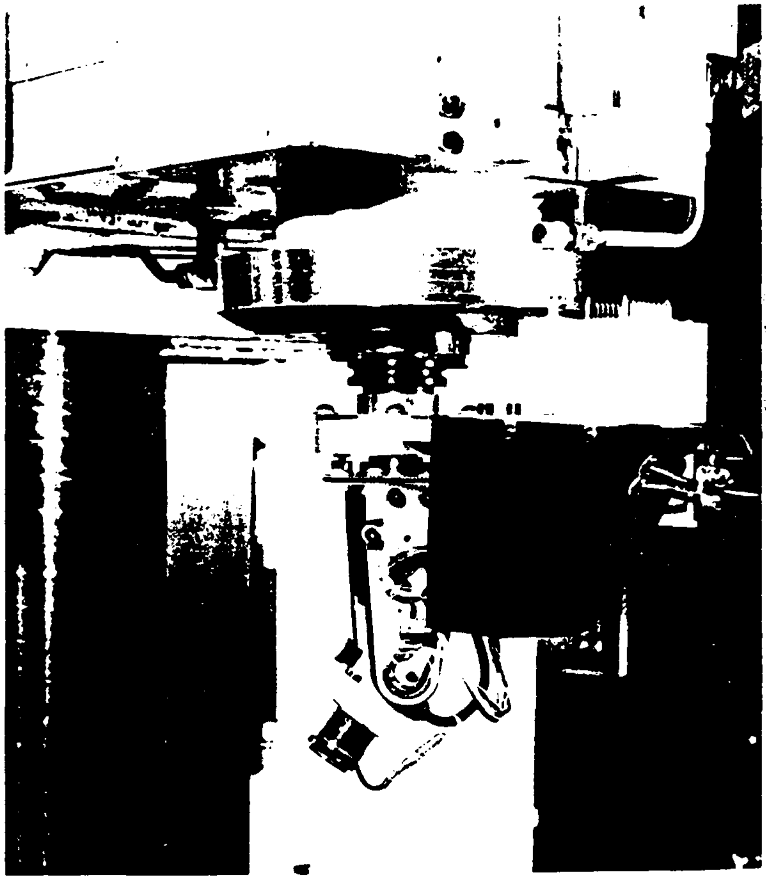

Figure 12- The tilt/pan mounted in the spindle

The tilt/pan camera mount was designed to supply the sensing expert with images of the machine tool environment. It has two servo controlled axes that are driven by permanent magnet electric motors. Limit switches on each axis are used to define the home position (proximity switches may be retrofitted at a later date). The tilt/pan was designed to precisely define the location of the image plane so that accurate measurements can be taken. The camera itself is quite small, housing just the lens and transducer. Signal conditioning and amplification is performed in a separate enclosure located at the top of the tilt/pan. The video signal is then conducted through the standard receptacle to a coaxial connector in the coupler box, and from there to image processing boards. The miniature size of the camera and the use of rare earth magnet motors reduce the overall size of the assembly.

In conjunction with the machine tool, the tilt/pan can be manipulated in the environment and its motions can be coordinated with those of the machine tool. A number of coordinated motions are supported by the control software. **Look**(x, y, z) instructs the controller to point the tilt/pan so that the location (x,y,z) is in the center of the image plane. The image may be reversed (upside down), but the image processing software is not affected by this. **Zoom**(x, y, z, %) first points the camera at a location in the workspace (x,y,z) and it follows a path towards that point, travelling (%) of the distance between the initial position and the destination. **Track**(*obj_x*, *obj_y*, *obj_z*

x,y,z) commands the tilt/pan to maintain the objective point (*obj_x, obj_y, obj_z*) in its field of view as the camera moves to a new position (*x,y,z*). Motions of the two axes of the tilt/pan are then coordinated with those of the machine tool. In-process measurements are not currently supported though they could be performed by mounting the tilt/pan in a fixed receiver in the machine tool workspace instead of the spindle (no cutting can take place with the camera in the spindle).

Tilt/pan detailed design description

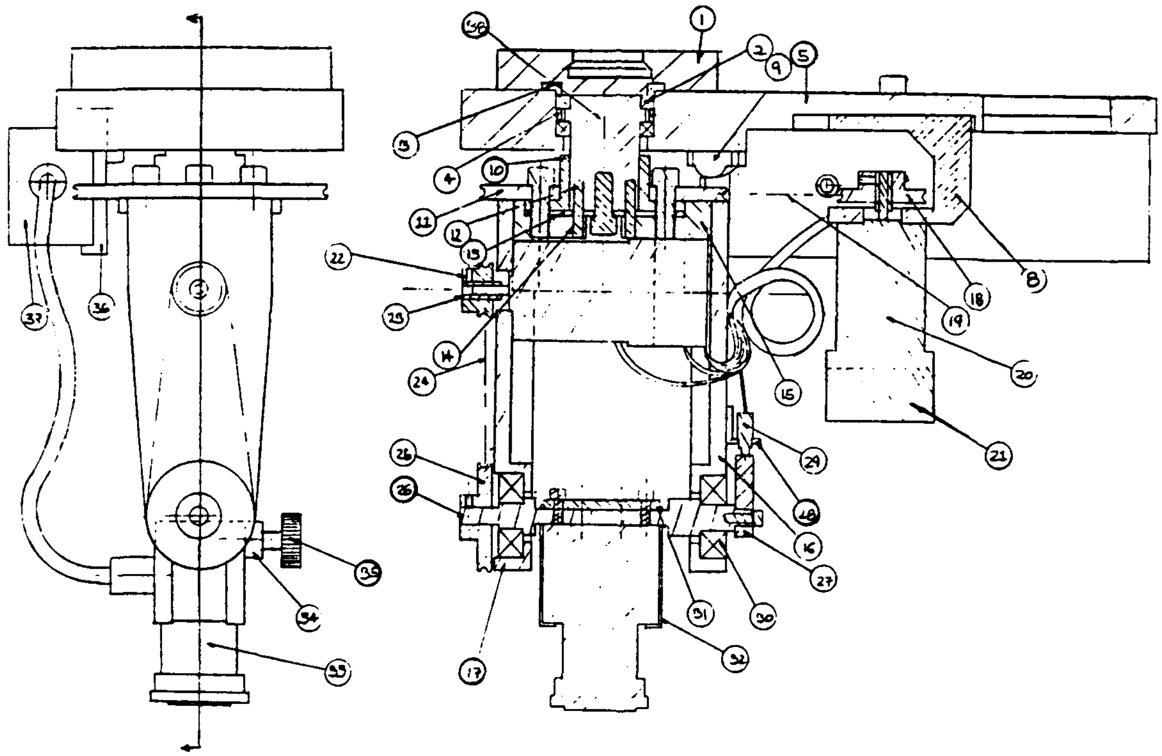

Figure 13- Design drawing of tilt/pan, covers removed

Please note that left and right in this description refer to the way they appear in the drawing. Also, a sheet metal cover that wraps over the two arms, and another that protects the pan motor and its mount, are not illustrated. The receiver for the standard receptacle, item #1, is attached to the main mounting plate #5. The signal conditioning box #37 is fixed to the main mounting plate by way of a small backing plate #36. Pan motor mount #18 is

bolted to the underside of the main mounting plate, using slots so that the drive belt can be tightened. The pan motor and encoder (#20 and #21, respectively) drive and measure the position of the small pan gear #18. Shaft spacers #23 are used for the small gears of both the pan and tilt axes. The flexible belt #19 wraps around the large pan gear #11.

The large pan gear rotates about its axis as defined by the pan shaft #38, which has two bearings #2 and spacer #4 to maintain perpendicularity. A large bushing #10 wraps around this shaft and holds the large pan gear parallel to the main plate #5. Four bolts in a circle around the large pan gear squeeze the bushing #18 and spacer plate #13 against threaded holes in the two upright brackets #14, #15. The gear, spacer plates and upright brackets are then bolted and pinned into the pan shaft #38. The upright brackets can then hold the two arms #16 and #17 parallel to the pan shaft.

The tilt motor and encoder are situated between the arms and are fixed by bolts that attach to slots in the left arm #17. The small gear for the tilt axis #22 drives large gear #25 by way of the flexible belt #24. The pan shaft #26 is driven by this gear, and rotates about bearings #30 pressed into the arms. Clips #32 and mounting block #31 are redundant methods used to hold the camera in place.

Limit switches are actuated by cams on each axis. The pan axis cam lobe #9 is fixed to the underside of the main plate. A barrel type limit switch #15 is held in a hole in the right upright bracket #15 by a set screw. The tip point is adjusted by moving the switch up or down within its hole and holding it with the set screw. A square slot in the tilt cam lobe #27 slips onto a mating feature on the tilt shaft #26. The tilt limit switch #29 can be adjusted by moving its mounting bracket #28 in its slotted holes.

Modular fixtures

The modular fixture set of the IMW addresses the need for fixtures that are flexible and capable of being assembled without human intervention, in a reliable manner. The tooling system consists of the tool base, passive elements, and active elements. It was inspired by the modular tooling sets available in industry today, though they have been redesigned for automation. They are assembled using the expanding finger novel tool, hence each component has a gripping hole located somewhere near its center of gravity. They all have pins that accurately locate them on the tool base or storage plate. They are affixed to the tool base using bolts that are tightened by the torque tool. The torque tool also applies the clamping force to active elements.

Through the use of modularity, adjustability, and machinable fixture components, a greater variety of fixture configurations can be produced with a fixed set of components, thus resulting in greater process flexibility. These fixture configurations can then hold specific workpieces for particular processing steps, as were planned by human or a computerized expert system.

Tool base

Modularity implies that objects in the tooling system can be precisely located and affixed to a range of other objects in a variety of orientations. These objects are the building blocks of the final setup. The tool base is the surface upon which they are assembled to make the final fixture. The tool base is attached to the machine tool. It consists of a grid of holes that can locate or affix components to it In the current model, 17 x 17 holes are laid out on a square grid with their centers .707 inches apart. When rotated 45 degrees, this hole spacing appears as nested rows of holes 1 inch apart.

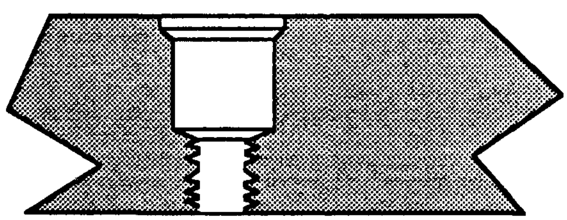

Figure 14- Typical hole in the tool base

Figure 14 shows what a typical hole in the tool base looks like. Three functions can be performed by the different features along its length. The first sixteenth of an inch in depth is reserved for hole covers. It is important to

manage the flow of coolant and chips as best as possible. Machining produces grime and debris that can compromise the performance of the system. These hole covers are intended to keep coolant and chips out of the holes when they are not being used. The hole covers have steel slugs within them so that they can be removed by an electromagnet, such as the one mounted on the tip of the torque tool. The rest of the cover consists of at plastic that seals and fits in its counterbore.

The next .500 inch of depth is devoted to accommodating locator pins. The precisely machined .5000 diameter reamed hole allows the pins to fit smoothly and with accurately, with half a mil clearance (.0005 inch). Objects mounted with a diamond and round pin will be minimally but completely constrained. When inserted by a gripper with compliance, such as the finger gripper, the mating parts are free to follow guiding chamfers and realign themselves as needed. The final feature in the one inch thick tool base is a #3/8-16 tapped hole. The thread size accepts bolts that are strong enough to resist forces typical in machining (up to 5000 pounds for our design).

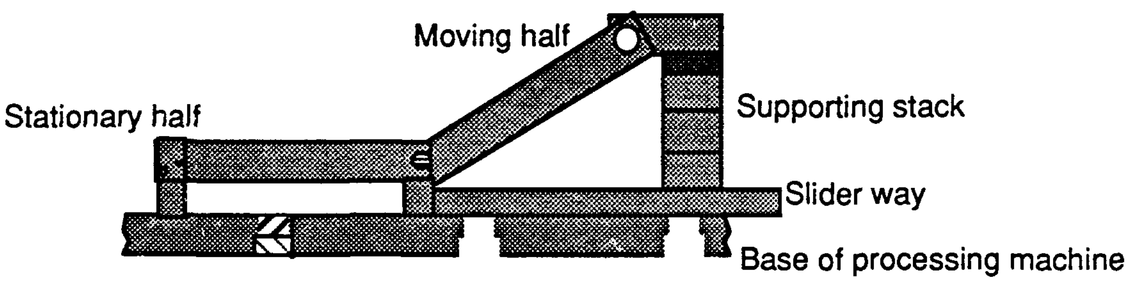

Figure 15- Repositionable tool base

Many features on finished parts can be more easily produced if the workpiece is oriented at a specific angle with respect to the tool that is processing it. Traditionally, machinists have used angle blocks to reorient the part to standard angles such as 45 or 90 degrees, or a sine plate to produce odd angles. The tool base of the IMW fixturing system (see figure 15) provides the flexibility of either approach.

The base is split into two halves, one of which can be lifted up to 100 degrees by a pneumatic cylinder. The two halves of the tool table rest on 1 inch thick supports and on the slider way. These supports are then connected to the machine tool. The spaces produced under the two halves are intended to allow for the flow of coolant and chips if the fixture is washed in between setups. When the tool table is raised, its slider way is exposed. On the slider are two reamed and one tapped hole into which components can be stacked

so as to create a support. The finger gripper can reposition the slider along its way so that the support stack is directly underneath the moving half when it is lowered. The moving half has a slot with a pin through it along its back edge (see figures 17, 18), and this is what comes into contact with the support.

Figure 15 shows how the table, stack, and slider way would interact. The tool table can easily assume final orientations from 15 to 90 degrees, thus reorienting the workpiece fixtured in it. By building the setup while the table is flat and then rotating it, angled features can be produced on the workpiece. In cases where standard angles are often used, blocks of a fixed size can be used to support the moving half. For less standard values, adjustable or machinable components can be used. These components offer a continuously adjustable range of heights, by trading off device complexity against processing time to achieve greater flexibility.

Adjustable riser

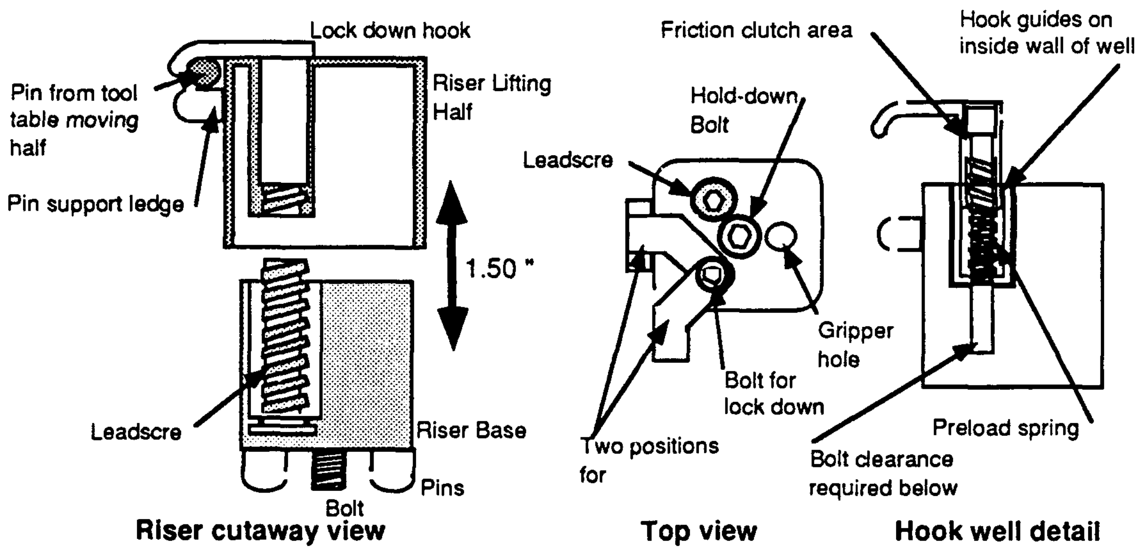

Figure 16-Adjustable riser conception

The *adjustable riser* (Figure 16) was designed to provide a continuously variable support that can be used to hold the tool table at odd angles. This device has not been built. The riser base has a leadscrew mounted in it that can be rotated by the torque tool. The riser base mounts to the tool base or slider using pins and a bolt, and guides the mating half along its outer side surfaces. The lifting half has a threaded hole that the leadscrew fits into, thus raising or lowering that half. This threaded hole is at the end of a deep well. This way the two halves nest when retracted, so as to be space efficient. The leadscrew is self-locking at whatever position to which it is set.

A second deep well on the raising half houses a rotating hook subassembly. The hook prevents the moving half of the tool table from lifting when upward forces are applied to the table. The hook swings 90 degrees for assembly and disassembly. By preloading the hook against its support using a spring, the hook can be made to rotate under friction at the top of its travel. It follow a straight line path downwards to hold down the tool table at the end of its travel. To reiterate, the raising half is thus an empty cube with one face removed, which fits over the base of the adjustable riser. Attached to the inside of the cube are two long bosses which fit into deep holes in the riser base. These bosses are actually slender tubes that hold the leadscrew and rotating hook.

Tool table detailed design description

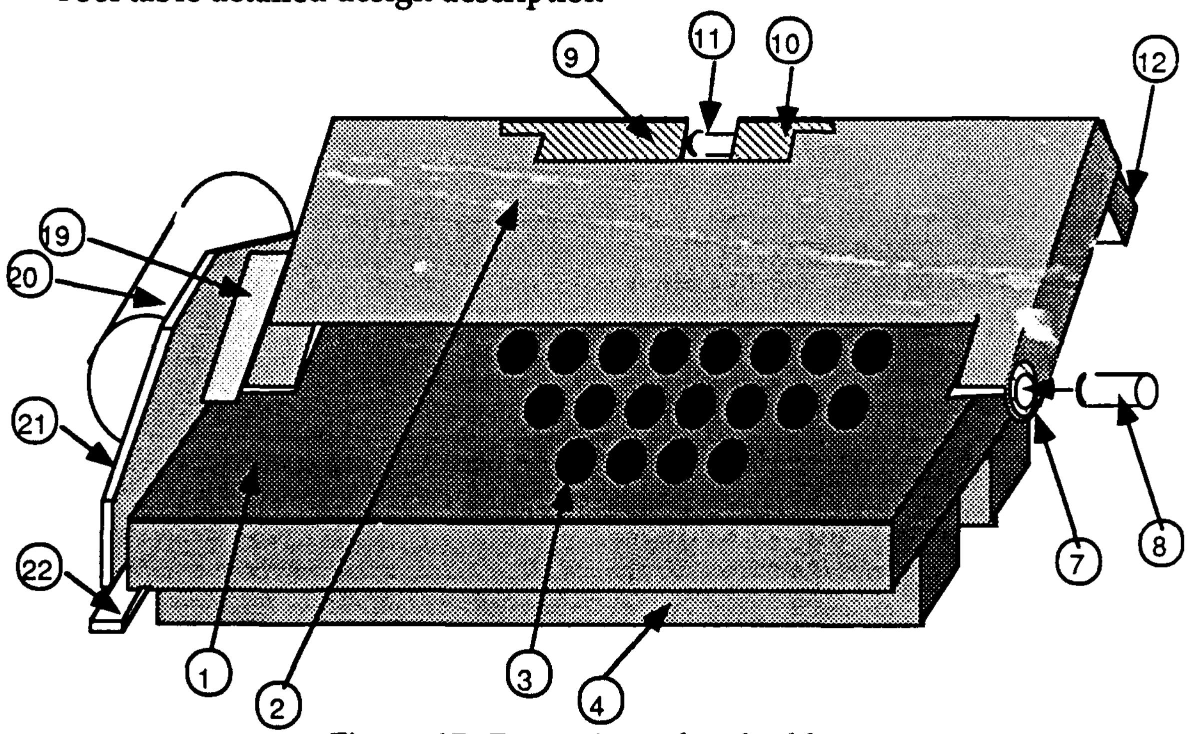

Figure 17- Front view of tool table

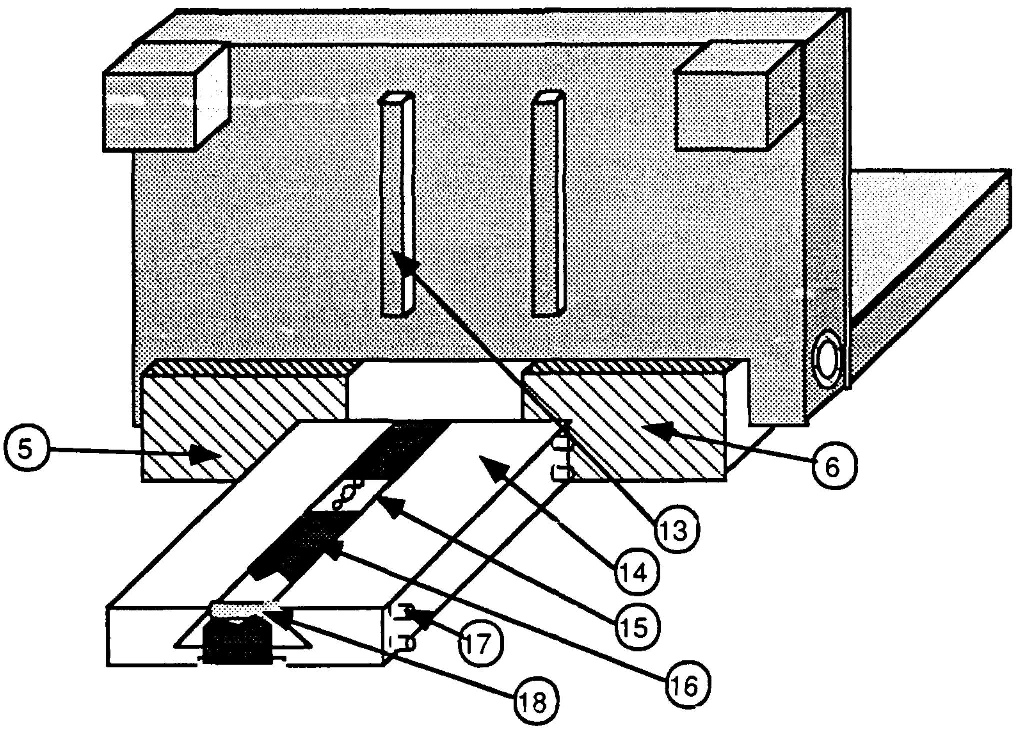

Figure 18- Rear view of tool table

The tool table design description that follows refers to the item numbers that are illustrated in figures 15 and 16. The main part of the tool base consists of two halves, items #1 and #2, on which a square grid of 17 x 17 holes has been placed. Each hole (refer to figure 1) consists of a .625 inch diameter by .063 inch deep counterbore into which hole covers item #3 are placed, a .500 inch diameter reamed hole that goes to .563 inches deep, and a 3/8"-16 tapped hole which goes from there to 1.000 inch deep, breaking through to the bottom of the plate. The stationary half rests on a front support item #4 and middle supports #5 and #6 such that it is raised 1.000 above the base of the machine to which it is attached.

The moving half has two short 'arms' into which bushings item #7 have been pressed. These bushings allow the moving half to rotate about .500 diameter pins item #8. The back edge of the moving half has two pieces items #9 and #10 bolted and pinned to it. These pieces hold a .375 inch diameter pin #11 such that it spans a 1.00 inch slot and runs parallel to the axis of rotation. The moving half is supported by the pins #8, the middle supports #5 and #6, rear corner supports #12, and rear mid supports #13, such that it is lifted 1.000 inch above its mounting surface.

The rear mid supports #13 rest upon the slider way #14 when is is in the down position. The slider item #15 that runs along the inside the dovetail slider way #14 has two .500 diameter holes for locating and one 3/8-16 tapped hole to hold and locate supports such as the adjustable riser previously

described. Its motion spans the length of the moveable half item #2. The slider way cover #16 is a kevlar reinforced teflon material that rides on four bushings #17 on the outside edges of the slider way. These bushings in turn rotate freely on pins #18 that span the gap on the top of dovetail. The moving half is lifted by the connecting arm #19, and this arm is driven by a rotary cylinder #20 with 100 degrees travel and a 2.0 inch cylinder diameter. This cylinder is supported by a vertical plate #21 which is bolted to a horizontal strip #22. This horizontal strip is independently affixed to the machine's base plate. The cylinder is powered by air that has been controlled by a four way solenoid valve, The four way valve is in turn electrically activated by a relay, so that the presence or absence of a 120 VAC signal raises or lowers the tool table.

Passive components

Passive elements define a precise location in space and resist forces applied by clamps or cutting tools. Three types of passive elements are currently used in the IMW tooling system and another two types are anticipated. The riser block, parallel, and straight locator elements have been built and are currently used in the system. The straight locator provides a solid contact that supports radially or vertically. Parallels are used to lift parts above the tool table a precise amount. The riser blocks are used to lift other fixture components to a particular height. They might be used to support toe clamps such that they can hold down a tall part, for example. Shoulder locators and vee blocks are anticipated but not yet implemented. Each passive component has a gripper hole and a pair of diamond and round pins to affix it to the base (locator pins, however, don't have two pins). Only the riser block is bolted down to the table, since the other elements do not experience lifting forces in normal operation.

Only a small set of sizes are available for the passive elements. This is done so as to reduce the storage requirements of these parts and also to reduce the number of different objects that the holding expert must consider. There are two ways to achieve a particular height using these components, by either stacking standard elements, or by using machinable elements. These two approaches can be combined by stacking a machinable element on one of the standard variety. Riser blocks and parallels can be stacked on top of each other, and locators can be stacked on risers.

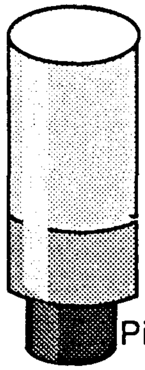

Figure 19- Machinable fixture components

The other way to get flexibility in passive elements is by machining them to suit the needs of a particular part. Simple fixtures such as the vise can be used to hold these *machinable fixturing components* as they are altered by processes so simple that their plans are trivial and can be stored as parametric NC machining programs. For instance, the height of a locator, parallel, or riser could be changed, the length of a bolt could be altered, or the width of a fence could be modified. Machinable components consist of a permanent base that contains locator pins and a hole for bolting it down (if appropriate), and features that locate and hold a soft, easy to machine material, such as aluminum (see figure 19). This material can then be machined, and the new height verified by a touch probe or other sensor, so as to yield a passive element whose dimensions are consistent with the requirements of the setup for a particular part geometry.

The accuracy of such machinable fixture components will never be as good as the ground and hardened surfaces of more permanent elements. However, the amount of uncertainty added to the final tool may still be considerably less than the tolerances stated in the specification of a desired workpiece. For instance, if the accuracy in machining the fixture components in a simple setup is $\pm$ .001 inch, parts accuracies to $\pm$ .005 inch will be still be possible. These figures are typical for both equipment capability and part tolerances.

It should be noted that only one level of recursion is being suggested; it is not advisable to make fixtures that make fixtures for the fixture. However, by giving the system the ability to alter its fixtures, a much wider range of parts can be held with no increase in the amount of components stored. These components are expendable, thus the materials and objects that are so modified must be relatively cheap and plentiful (such are aluminum rods, or standard bolts).

Active components

The active components apply the clamping force that holds the workpiece down as it is experiencing cutting forces and vibrations. Since these forces can be quite large, the toe clamps were designed to be able to apply up to 1500 pounds to the workpiece. Due to its greater dependence on friction, the vise was designed to deliver 5000 pounds force. Both of these clamps can be manipulated using the finger gripper and bolted down with the torque tool. A precise holding force can then be applied by controlling the current going into the motor. Hence brittle or thin walled workpieces can be held without damage. The leadscrews that convert rotary to linear motion are held in their final position by friction between the thread and nut, so that the computer controlled torque tool can record the final rotary position of the screw. The clamps are thus self-locking, and do not require bulky hoses or cables that clutter the workspace and can get damaged by the cutters.

Toe clamp

Toe clamps come in a number of styles and are available for both traditional and modular tooling. They have all been designed to be assembled by a human operator. The basic function of the toe clamp is to apply a large downward force on a workpiece such that it remains stationary as it experiences forces from the cutting tool. This loading must be within bounds, or else the surface of the part will be damaged. The toe location is selected by the tool designer according to a few heuristics and will vary between parts, operations, and tool paths. It is desirable to have as compact a toe clamp as possible so the maximum surface area of the workpiece is exposed while still applying a large force in a variety of configurations. The method of actuation of toe clamps is usually either by power screws or hydraulic cylinders.

The toe clamp was designed to apply up to 1,500 pounds of force onto a workpiece. In order to keep the clamp as compact as possible, C-250 maraging steel was specified for most load bearing parts. It has a yield strength of 250 KSI. The overall height of the toe clamp is less than 2.50 inches and its footprint is 3.5 x 2 inches, excluding the extendable arm. The arm radius can vary from 1.625 to 2.4 inches, the toe angle ranges from -50 to +50 degrees and workpieces from 0 to 1 3/8" thick can be clamped without needing to lift the toe clamp on risers. The toe clamp is precisely located by a diamond and round pin, and bolted down with two standard 3/8-16 bolts. The location and size of these features permit the toe clamps to be inserted in the base of the tooling system previously described, in four orthogonal orientations

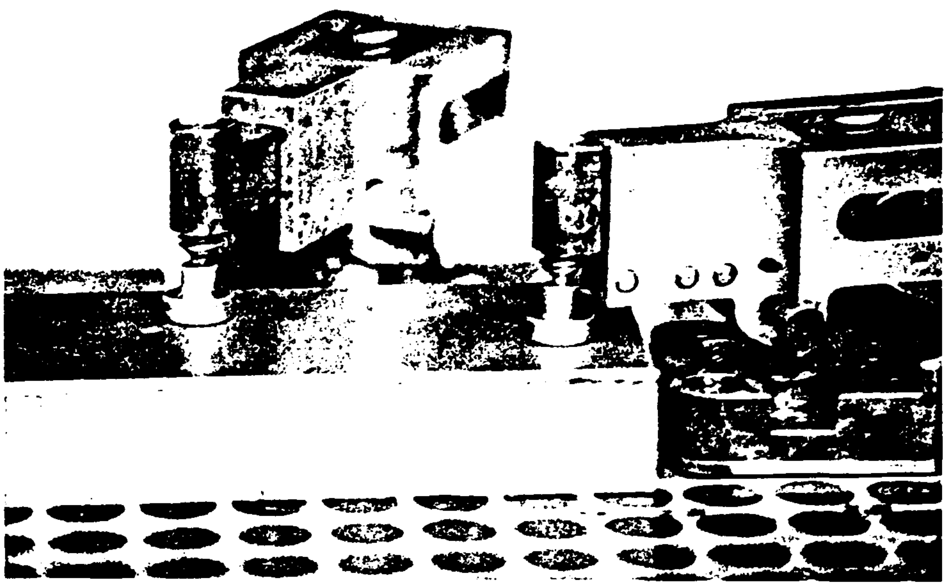

Figure 20- Toe clamps holding a part

The toe clamp, shown in figure 20, can be actuated and manipulated manually or automatically. The toe is repositionable in three degrees of freedom. The workspace of the toe clamp is spherical, with adjustable radial position and angle, and attitude angle. A leadscrew behind the attitudinal axis of rotation is used to change that degree of freedom, and when the toe contacts a workpiece, the clamping force is applied to the part through this screw. It has hexagonal socket 'burned' (by EDM) into it so that the lowest possible profile is maintained. A hole has been placed above the toe so that griper the finger gripper can move it in the horizontal plane, thus changing the radius and angle of the toe with respect to its base. These two axes of rotation are dampened by spring plungers that act to increase the coulomb friction that must be overcome in order to move the clamp. They are necessary so that the toe remains at the position it was last placed. In this way, the use of sensors is avoided.

The leadscrew can be driven by the torque tool, in which case the applied force is precisely controlled, thereby avoiding damage to the workpiece surface. The swivel pad used on the clamp also distributes the forces somewhat. The acme screw is self-locking so that the power source (torque tool) can be disconnected during machining. This is an improvement over hydraulic clamping systems, which can give a precise force but must be connected with bulky hoses. The rotational position of the toe clamp can also be changed by the torque tool, in which case it is not necessary to have the clamp's attitude set to zero. Thus the toe can be lifted up to as to make the insertion of the workpiece easier, and then swung around and lowered in one motion by the same tool. Otherwise the [illegible] clamp arm must be [illegible] in order to change its angle and radius with the finger gripper.

In summary, the repositionable toe clamp for automated setups was designed to be compact, rugged, and capable of being loaded, positioned, and actuated by manipulators and other tools. It is compact and flexible, so that it can also be useful in completely manual applications. It can be actuated with common hand tools, and when a precise torque is applied by a torque wrench, the output force can be known. With only minor modifications, this toe clamp could be used with other modular tooling systems.

Clamp detailed design description

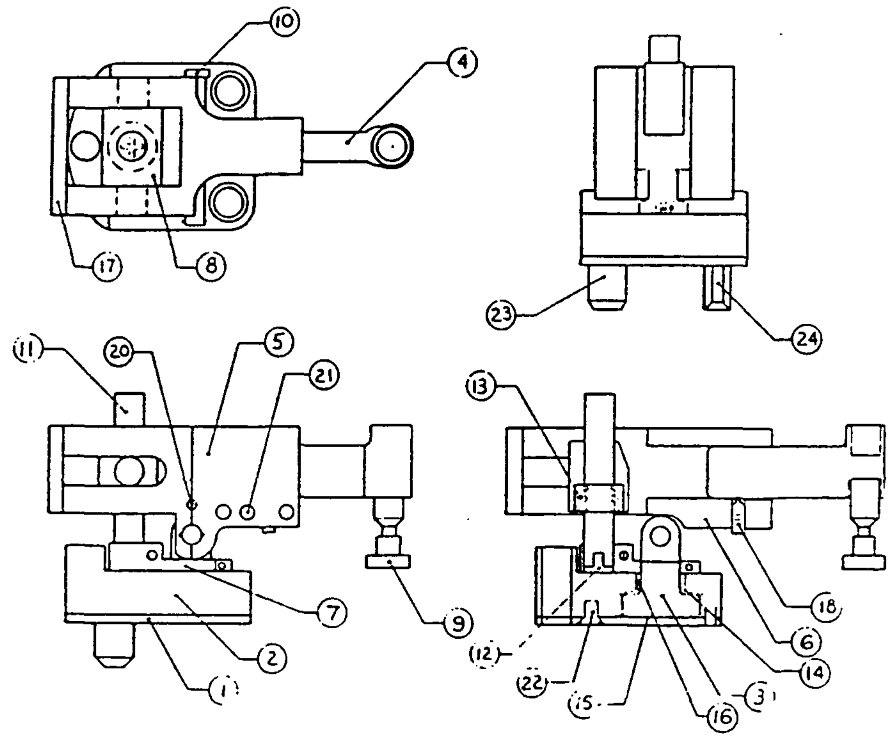

Figure 21- Original assembly drawing

The item numbers in this description refer to figure 21. The toe clamp base item #2 has a hole for the finger gripper, and a counterbore on the other side into which the neck #3 and bearing washers #14 and #15 are fit. Bottom plate #1 insures that this assembly is tight. Locator pins #23 and #24 are pressed into base plate #2 to anchor the clamp in the tool base. Atop the swivelling neck #3 is a hole through which the arm pivot pin #10 is placed. This pin allows the arm holder #5 to rotate about it. Slots in the rear of the arm holder #5 permit the acme pivot #5 to travel laterally with respect to the arm holder. This freedom of motion is required for the arm holder to rotate up and down.

The acme pivot then raises or lowers the arm holder as the leadscrew #11 is rotated. Lateral forces are generated when a force is applied to the toe clamp

while the attitude angle is not zero. This moment is resisted at the base of the leadscrew by the keeper piece item #7. This keeper has been redesigned to fit snugly into a circular slot on the top of the base #2 (N.B., the slot is not illustrated). This keeper also prevents the leadscrew from lifting up. The 'toe' that contacts the part is a swivel pad #9, and it is mounted in the arm item #4. The arm fits in a deep slot in the arm holder, and captured by arm holder bottom plate item #6. The arm holder and its bottom plate are held together by pins #21. A ledge on the arm #4 contacts a similar ledge on the bottom plate so that the arm can not be pulled completely out of its holder. Additional friction is added to the radial and angular degrees of freedom of the arm by the use of two spring plungers item #21.

Vise

The vise is a versatile fixture capable of holding a wide variety of parts, though it is often used with prismatic workpieces. It is capable of both holding and locating a part when properly used. The three main components of a vise are the fixed jaw, a moving jaw, and the base plate that holds them together. In some instances, the base plate is discarded and the two halves are secured to the work table independently. The maximum size part that the vise can hold is a function of the width between the jaws and the size of their faces. With a split vise design (no base plate), this jaw width can be made to vary considerably. The jaws of the vise may have special features such as a ledge to lift parts above the workpiece so that they are still parallel to the work table, or vee blocks to hold axially symmetric parts, such as cylinders or pipes. These features considerably extend the range of part shapes that the vise can hold.

The vise is probably the most commonly used fixture because the jaws can define up to all six position coordinates while holding the part. However, the part is usually 'indicated in' in at least one direction. For example, a measurement of part location is often required along the axis parallel to the jaw faces since most vise jaws don't have stops in that direction. The vise exposes the entire top face to the cutting tool, which can make for more efficient production plans. It relies on friction to hold the part, so the applied forces must be very high. It is important that the fixed jaw not deflect excessively since this would disturb the location of the workpiece. A undesirable quality of many vises is that they lift the part off the supports just as the final clamping force is being applied.

Our new sensor based vise fills the requirement for a vise that is capable of all of the traditional functions, and new functions that make such a device practical in an automated environment. These new functions include automating assembly and actuation, controlling forces applied to the part, and monitoring motion of the part during machining.

Adjustable clamping forces need to be selected and applied in order to machine fragile parts. The sharpness of the cutting tool, chatter and fixture rigidity must often be verified in automated environments. These conditions can be inferred from measurement of part vibrations. A method of electrically connecting the sensors to their amplification circuits is also needed and included. Even in manual applications, this new vise is of value. It has its own design feature to prevent part lifting. Also, it could be easily modified to be used with other vendor's tooling sets.

The reconfigurable vise was designed specifically for use in the automated setup workstation of the IMW. It is actuated by the torque tool or hand tool and can deliver a force of up to 5000 pounds to the workpiece with minimal deflection. Its jaw size is 2 inches by 4 inches. For its capacity it is quite compact; the moving jaw is 3.25 inches high and has an unextended footprint 5 inches long by 4 inches wide, while the fixed jaw is 2.375 inches long by 5.25 inches wide. When the torque tool is used, the clamping force can be controlled so as to minimize part bending.

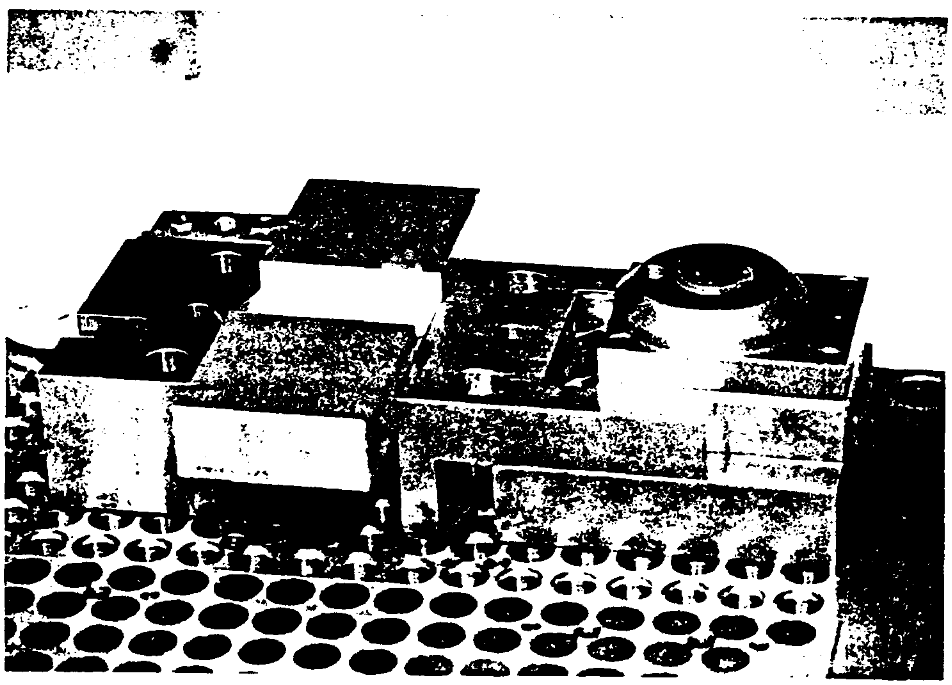

Figure 22- The reconfigurable vise

The vise, shown in figure 22, features interchangeable jaws on the moving half. These jaws can be assembled with a simple vertical insertion that the finger gripper can perform. It is split into fixed and moving halves, and they are designed to be inserted into the tool base that was previously described. The split design plus interchangeable jaws increase the amount of flexibility

that can be generated in fixturing without needing craftsmen to set them up. The fixed and moving halves also have holes for the finger gripper, and chamfered pins underneath, so that they may be assembled by the novel tools.

The moving half of the vise has a diamond and round pin pressed into its base so as to anchor it at a precise location in any of four orthogonal orientations. It is driven by a leadscrew that is self-locking, hence power does not have to be connected to it during machining. Power is transmitted to the leadscrew by way of a spiral bevel gear pair that redirects the torque 90 degrees. The input bevel gear has a hexagonal slot burned in its center, so that the torque tool or simple hand driver can actuate the vise. The moving half travels .750 inch, so that it spans the distance between hole centers in the tool base.

The jaw on the moving half is removable, so that other jaws can be inserted, which might have a ledges or vee notches, for example. It is also possible to use machinable jaw blanks that can be altered to conform to an irregular part shape. The moving jaw is pushed downward by an angled piece attached to the end of the leadscrew. Also, the leadscrew is situated as close to the top of the jaw as possible. These two features force the workpiece down and against its vertical locators, thereby avoiding the 'lift-up' problem. When retracting, the moving jaw is drawn backwards by a hook-like protuberance. The moving half and fixed half are both made out of common cold rolled steel, with the gliding and jaw surfaces ground to enhance their precision.

The fixed jaw of the vise has two sensors mounted in it that measure low and high frequency vibrations. The acoustic emission sensor can monitor frequencies up to 200 KHz and responses measured at this bandwidth can give important clues to the nature of the cutting process, such as the sharpness of the tool, quality of the workpiece material or presence of cutting fluids. The second sensor, an accelerometer, measures lower frequency vibrations that can indicate whether the tool, fixture, and part are rigid enough, or whether the tool is broken, absent, or jammed.

These sensors need to be electrically connected to their amplification circuits, and this can be performed automatically. Thus, no wires or cables have to extend from the vise when the sensors are not being used. A shielded plug and receptacle are used for this connection. The plug can be vertically inserted by the finger gripper, and its path is guided by chamfered pins. The cable to this plug is stored on a spring tensioned take up reel, and the cable routing can be selected to minimize clutter.

The acoustic emission sensor must be pressed directly against the workpiece for best signal capture, with a force on the order of 15 pounds. The sensor must completely contact the part, so plans for placement of the part on the jaw should consider this constraint when measurements are needed. It is

equally important that the sensor be fully retracted when not in use, and during part loading, so that it is not damaged. For this reason, a cam and follower mechanism have been included to force the acoustic sensor against the part. This self-locking cam has a hexagonal slot burned in it so that the torque tool can rotate it, and thus retract the sensor.

Moving half detailed design description

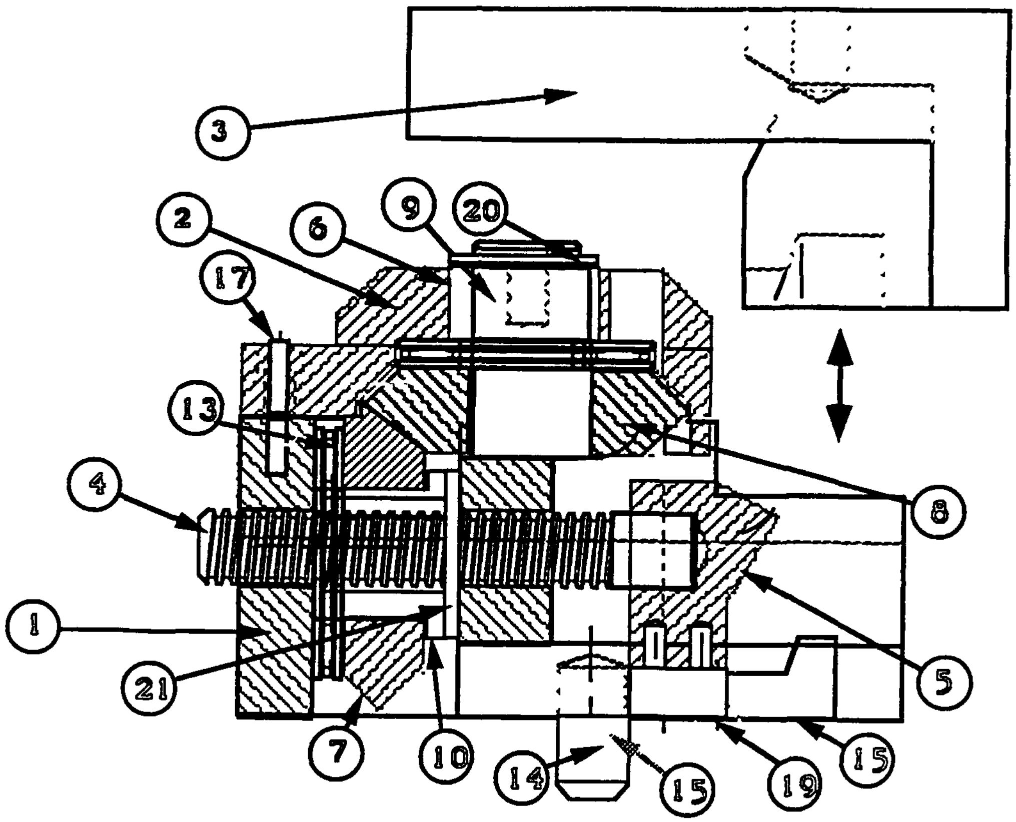

Figure 23- Assembly drawing of moving half, jaw removed.

The base of the moving half is called the glide structure, item #1. Diamond and round pins items #14 and #15 are pressed into its bottom so that the vise can be accurately located on the tool table surface. Gear mount item #2 is pinned and bolted to the glide structure, and serves to cover the transmission components as well as holding the input bevel gear item #8 in place. It also has a hole in it suitably placed for use as a manipulation feature for the finger gripper. This gear is captured by the input torque shaft #9 which has been pressed into the center of the gear. This shaft has a hexagonal socket burned in it so that it can be rotated by hand or power tool. A retaining ring item #20 holds the input shaft within the bushing item #6, and thrust bearing item #13 allows the input gear and shaft to rotate freely.

The lead screw item #4 that applies forces to the movable jaw #3 is driven by the output bevel gear #7. This gear meshes with the input bevel gear, and is free to rotate on thrust bearing #13. Its axial position is maintained by washer item #21. When rotated, the flanged acme nut item #10 causes the leadscrew #4 to impart a linear motion on the force applicator #5. The leadscrew position is maintained by two close fitting holes on the glide structure #1, the acme nut #10, and the force applicator #5. Below the force applicator, the jaw retracting hook #18 is mounted so that the moving jaw item #3 can be pulled back. Both the force applicator #5 and the movable jaw #3 slide along surfaces of the glide structure #1, and these bearing surfaces have been ground on both parts. The force applicator #5 exerts a forward and downward force on the movable jaw #3 such that a part held in the vise is clamped and does not tend to lift off of its supports.

Stationary half detailed design description

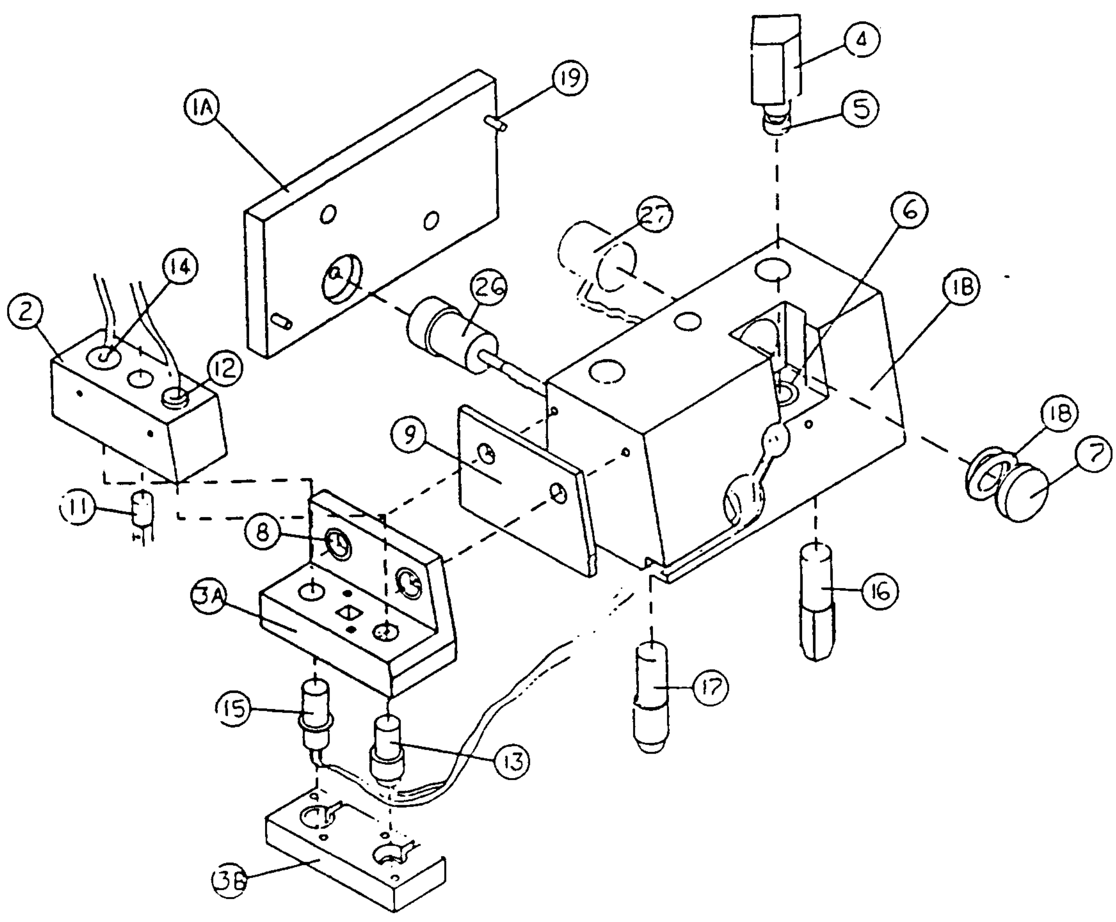

Figure 24- Exploded view of fixed jaw

The principle member of the fixed jaw is the rough body item #1B. It has diamond and round pins items #16 and #17 pressed into its bottom in order to anchor it. The front plate of the body, item #1A, is the member that contacts the part, and is bolted and pinned to the rough body item #1B. The accelerometer item #26 is threaded onto this plate so that low frequency vibrations from the part can be measured. An acoustic emission sensor is made to pass through the front plate #1A so that it directly contacts the workpiece (N.B. there is a hole missing in the drawing of part #1A). It can be extended or retracted by rotation of the cam item #4 and #5. The cam #4 has a hexagonal socket burned in it so that it can be rotated by tools. It is held in place by a bushing item #6 and a set screw.

Rotation of the cam #4 causes the cam follower #7 to compress a spring item #18 so that the acoustic sensor is forced against the workpiece. Then high frequency vibrations of up to 200 KHz can be monitored during the machining process. Slots on the beveled rear face of the the rough body #1B are provided for cable routing. These wires lead to shielded connectors #13 and #15, which are situated on female coupler bottom #3B and in female connector top #3A. Items #3A and #3B are electrically isolated from the rest of the vise by insulation plate #9 and insulation bushings #8. The male coupler #2 houses two male connectors #14 and #15, and the modified socket extension #11 guides items #2 into item #3A to connect the sensors to external amplification circuits.

Concluding remarks

In this report the mechanisms used to create an automated setup assembly system have been described. These include a fixture set that is designed for automated assembly and the tools used to construct them. These devices, located in the workspace of a NC vertical milling machine, combine to create a modular, reconfigurable world in which uncertainty has been significantly reduced. In the process, the machine tool is transformed into a robot, an assembly station, and an inspection station, besides its traditional function as a metal cutting machine.

This system represents an example of a craftserver, a concept that has been introduced to describe physical transformation engines for automated manufacturing planning systems. The craftserver is designed specifically to work with one or more expert systems so that their plans can be executed. A full description of the controlling program of the craftserver, and the overall architecture, is found in a separate technical report [10]. The concept has applicability well beyond machining; craftservers can be combined with press brakes, welding systems, plastic or metal molding machines, as well as flame,water jet, or laser cutting systems.

The Intelligent Machining Workstation is a combination of a craftserver to automate the creation of setups and a collection of domain-specific process planning expert systems. Together they form a system that is capable of producing a wide variety of part styles in extremely low batch sizes, to the point where automated production of single unit quantities is practical. The ability to produce parts in such small volumes can have a positive impact on the creation of prototypes, repair parts, molds and dies, and give manufacturers the ability to respond more rapidly to the needs of their markets.

By integrating so many different functions on one machine tool, the amount of metal cutting time and hence the traditional metric of machine utilization is decreased. However, when compared with the traditional, manual method of creating single unit quantities, production efficien actually increases. This is especially true when the time required to create a process and generate the NC code is considered. Also, by taking advantage of the full potential of the machine tool, costs are reduced, such as those associated with an additional robot, measuring machine, or material handling systems.

Flexibility is relative a term that is best used when comparing systems. No machining cell is so adaptable that both aircraft wing spars twenty feet long and escapements for Swiss watches can be produced by the same system. Beyond this issue of part size, the diverse nature of the bounding envelope of

different parts limits practical flexibility. For instance, while cylindrical parts can be fixtured with vee blocks and then machined on a vertical mill, it is impractical. In order to reduce the complexity of machine tools, the number of fixturing components, and search space of expert systems, families of part styles can be classified and used as boundaries between systems. Group technology schemes [56] can be developed for a particular manufacturer's mix of parts so as to yield practical systems that span the full space of products made in any one factory.

Development of expert systems that can generate valid holding plans is equally important to the goal of physical automation. Kinematics, solid mechanics and computational geometry are domains that have been more amenable to analysis than synthesis. While important strides have been taken towards development of successful holding expert systems have been taken, more research in this domain is required.

All mechanisms described in this report have been built and individually demonstrated. However, system reliability is still not optimal. Several minor design changes have been identified to correct these deficiencies. Also, stock manipulation must still be performed manually. Fixtures still cannot be reoriented due to the lack of a three degree of freedom wrist, though this could be added at a later date.

The most significant aspect that has not been fully addressed is the problem of chip control. Chips, coolant, and swarf must be removed from the environment in order for repeated fixture assembly to be achievable. The current prototype is configured on a vertical mill, where the chips fall directly on the workpiece and fixture. Future systems may be more successfully implemented on horizontal milling machines, where the chips fall away from the fixture. The use of chip breaking tools could also be helpful. One novel concept would be to integrate a chip wash hood as part of the machine tool. Here, the hood is lowered over the tool base and omnidirectional sprays dislodge the chips using coolant supplied by the machine tool as the working fluid. Another approach would be to have vacuum or directed coolant spray novel tools as part of the system.

Several deficiencies in present-day machine tool controllers have been identified as hindering the productivity of the current prototype. The machine tool had to be "hot wired" in order to allow for its external control by an independent computer. Wait loops in the controller that were originally intended to avoid double-striking of console keys are on the order of one second per keystroke. This slows down communications and, by extension, the assembly process. Also, low level information such as the position of the machine tool axes is displayed on a CRT and is not available to external controllers. These problems could be avoided if open-system architecture controllers were used. Such a UNIX-based controller has been

built at New York University [57] for the control of a three axis milling machine and make external control, interfacing to expert systems, and access of low level data much easier.

The greatest degree of success in flexible automated systems will be achieved when the entire design to manufacture process is integrated. In the fixturing domain, parts can have features added early on in the design process that simplify automated fixturing. Tabs and bosses can be used to hold down irregularly shaped parts. Through holes on workpieces can be used to attach plates that are easier to fixture and will hold the part as it is being machined. In the planning domain, designers who describe a new part by its features instead of just the basic geometry will provide much more useful information to automated process planners.

In summary, the fixtures and assembly tools described in this document have been demonstrated to be successful in the fixturing of a limited number of prismatic parts that can be machined in an NC vertical mill. Additionally, we have identified a number of issues that need to be addressed in order to make this hardware more practical for industrial users. This hardware, when linked to expert systems such as are provided in the IMW, provide enough flexibility to allow for the automation of single unit production volumes. This gives manufacturers the ability to respond more quickly to changing market demands.

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Tim Snodgras-	Vise fixed half
Barry Taylor -	Tilt/pan and coupler box

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